Columbia University Lectures

LIGHT

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1908–1909

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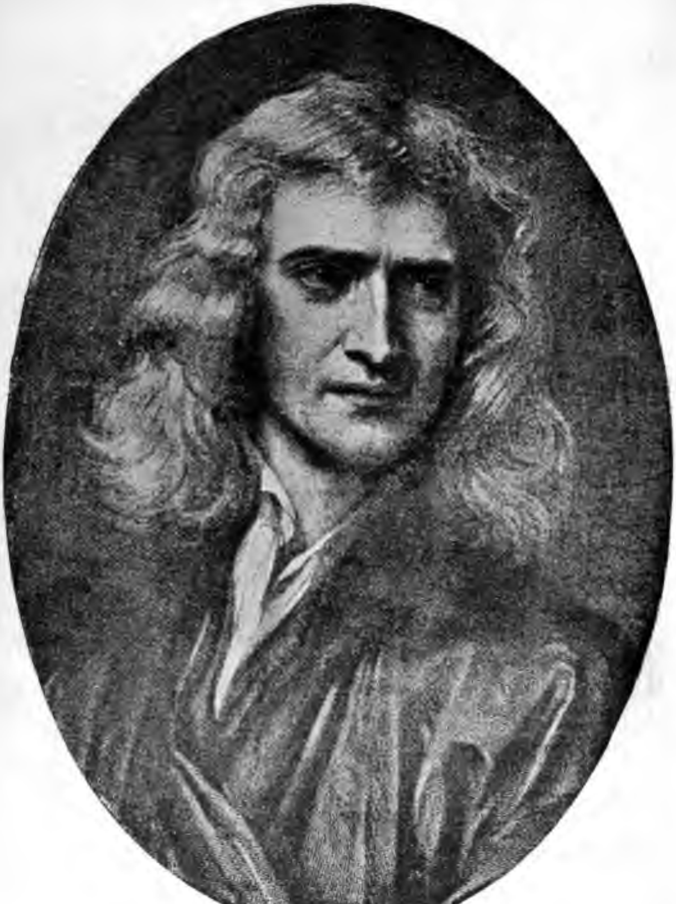

NEWTON

COLUMBIA UNIVERSITY LECTURES

LIGHT

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PREFACE

These lectures were given at the American Museum of Natural History during the winter of 1908–9, when I had the honor of occupying a chair of Mathematical Physics at Columbia University in the City of New York. It is not easy, in such a place, for a man of science to sit in cloistered calm, far from the distractions of the busy world of action, and to pursue research merely for self-illumination or for the edification of a caste of intellectuals. The throb of life is all around him, and it impresses him with the duty of responding to the demands of an active-minded people for reliable information on the most recent developments of science. He is expected to know; but not only to know, but also to communicate. And so, on being invited to give the Jesup Lectures, I attempted to describe the salient features of the modern theory of light within the narrow compass of ten lectures, and undertook in doing so to avoid technicalities as much as possible. I have had specially in view the man of intelligence who lays no claim to scientific knowledge, but who wishes to know what all the talk of science is about, and, in particular, why the physicists make such strange postulates as ether and electrons, and why they have so much confidence in the methods that they employ and the results that they obtain. For this purpose I have had to show him how wonderfully the theory fits the facts, down to the minutest numerical

detail; although, of course, the full force of the argument is lost owing to the necessity of eschewing mathematics and merely stating the results of theory without giving the actual demonstrations, except in the simplest cases. I hope, too, that the book may be found useful to the large body of teachers of physics throughout the country. They will find in it much that is scarcely touched upon in the ordinary text-books, and their appreciation of the difficulties of presenting such a subject in non-technical language will put them in that sympathetic frame of mind that helps so much towards the understanding of a writer.

My thanks are due to Mr. Farwell for the care and skill with which he conducted the experiments that illustrated the lectures, and to my colleague, Professor E. F. Nichols, for reading the proof-sheets and displaying a keen interest in the progress of the course.

R. C. M.

"A man of science does well indeed to take his views from many points of sight, and to supply the defects of sense by a well-regulated imagination; but as his knowledge of Nature is founded on the observation of sensible things, he must begin with these, and must often return to them to examine his progress by them. Here is his secure hold; and, as he sets out from thence, so if he likewise trace not often his steps backwards with caution, he will be in hazard of losing his way in the labyrinths of Nature." — *Colin Maclaurin: An account of Sir Isaac Newton's Philosophical Discoveries.* (1748.)

CONTENTS

LIGHT

I

EARLY CONTRIBUTIONS TO OPTICAL THEORY

"THEY tell us," said Matthew Arnold, "that when a candle burns, the oxygen and nitrogen of the air combine with the carbon in the candle to form carbonic acid gas. — Who cares?" I recall the story not with the object of revealing flaws in the chemistry of the brilliant advocate of sweetness and of light, but because it suggests an attitude to science that is far from rare, even amongst people of intelligence to-day. They tell you, sometimes frankly, but more often by implication, that they care for none of these things. Perhaps it is worth considering for a moment to what this attitude is due. Doubtless it springs from a variety of causes, according to the infinitely varied constitutions of the minds and hearts of the different thinkers; but in nine cases out of ten its origin can, I think, be traced either to misconception or to ignorance. Men are engrossed in other affairs; they know of science only by scraps, an occasional lecture, perhaps, or a magazine article read to lessen the tedium of a railroad journey. At the best they get a sight only of a portion of any one science, never a clear view of the whole structure. Now modern science is an elaborate work of art, and to be thoroughly appreciated it must be looked upon as a whole. Who that

has any eye and mind for the beautiful, and that finds himself in the presence of a great master, such as Rembrandt, will rest content with so distant a view or so hurried a glance that he can see only the outline of a hand or the contour of a cloak? The mind that can really carry out the process suggested by the phrase *ex pede Herculem* is not only rarely gifted, but must have been trained with unusual care. In a million, not ten that see only the foot will have anything but the vaguest vision of the whole man Hercules. The rest will turn aside with apathy and murmur, "Who cares?"

Bearing these facts in mind in this course of lectures on *Light*, I shall try to give you something more than a glimpse or two of single portions of the great scientific structure. Our view must necessarily be very incomplete, for to visit every portion of the building and study it with thoroughness would require the devotion of a lifetime. At the best I can take you along the corridors and let you see into some of the principal rooms. Enough, I hope, to enable you to grasp the main features of the plan and to put you in a position to appreciate the genius of the architects, and to realize something of the patience and endurance required to overcome so many obstacles and to build so solidly and well. If, however, there is any here, as I sincerely hope there is, who craves for more than this, and, not content with general outlines, wishes to probe into the very heart of nature, then, although I wish him all joy and success in his quest, I think it right to warn him that he must not expect very much from such a course as this. As Euclid said to the Egyptian king inquiring for a short cut to the mastery of geometry, "Sire, there is no *royal* road thereto." Indeed, hard is the road and narrow the way,

and to follow it to the end requires a clear head, and above all a stout heart. At the best I can put you on the way.

I have suggested that some men turn away from science through the mere scrappiness of their knowledge, but this is not the only thing that renders its pursuit unattractive. Many poetic natures find it cold and inhuman. Recall the query of Keats:—

> "Do not all charms fly
> At the mere touch of cold philosophy?
> There was an awful rainbow once in heaven;
> We know her woof and texture. She is given
> In the dull catalogue of common things."

The complaint seems to be that science, with its cold analysis, robs us of the pleasing sense of awe and mystery; but if you dig deep, you will find still enough of mystery left to satisfy the keenest yearner after half lights and the obscure. At the best, science only replaces one mystery by another of grander order.

As to the alleged inhumanity of science, the charge is probably made by way of protest against the attitude of some who, in the generation just past, made exaggerated claims in the name of science. They professed to worship Nature and to worship her so jealously as not to tolerate the worship of any other gods besides. They disparaged those human studies that have occupied men's minds throughout the ages, and were so far from believing that "the proper study of mankind is man" as to give the impression that that was the one kind of study not worth pursuing.

Such extreme opinions are naturally resented by the Humanists, who hold that "man hath all which Nature

hath, but more, And in that *more* lie all his hopes of good." The controversy is fortunately dead by this time, when science has become more genial, and it is seen to be absurd to make an arbitrary separation between man and nature. Apart from this, it is an obvious truism that a *science* such as that of light is a purely human study; it is taken up with discussions as to what *man* has thought of one of the most impressive of his sensations, so that the study of its history proves of intensely human interest. Here we watch the race grappling with great intellectual difficulties, and we see the spectacle of her champions painfully but surely overcoming countless obstacles. Each of their victories is a genuine victory of the spirit, each of their defeats a spiritual chastisement.

Others who stop short of charging science with inhumanity, think that its study robs men of their natural powers of appreciation. They point to the pathetic case of Darwin, but it would be easy to quote many great names to show that Darwin's experience, even if it has not been misunderstood, is extremely unusual. It would indeed be a terrible price to pay for our exact knowledge of optics, if it robbed us of our due joy in color and in light. Fortunately, however, there is not the slightest reason why, after pondering over the laws of light, we should appreciate less the brilliance of a New York sky or the glory of the autumn tints in the woods around us. Our study should rather increase our interest and our capacity for appreciation and enjoyment. It is strangely true, however, that artists have often an antipathy to the science — and this in spite of the fact that the problems that they have to face require for their solution an accurate knowledge of many optical laws. Few men knew better than Ruskin that between

wise art and wise science there is essential relation for each other's help and dignity, and yet even he seems doubtful as to the benefit of scientific knowledge to the artist. His lecture on the relation to art of the science of light is unusually diffuse (it deals almost as much with snakes as with either art or science), so that it is difficult to gather here anything relevant to the present discussion. In another place, however, he says plainly that scientific knowledge may be positively harmful to the artist. "The knowledge may merely occupy the brain wastefully and warp his artistic attention and energy from their point. As an instance, Turner, in his early life, was sometimes good-natured, and would show people what he was about. He was one day making a drawing of Plymouth harbor, with some ships at the distance of a mile or two, seen against the light. Having shown this drawing to a naval officer, the naval officer observed with surprise, and objected with very justifiable indignation, that in the picture the ships of the line had no port-holes. 'No,' said Turner, 'certainly not. If you will walk up to Mt. Edgecomb, and look at the ships against the sunset, you will find that you can't see the port-holes.' 'Well, but,' said the naval officer, still indignant, 'you know the port-holes are there.' 'Yes,' said Turner, 'I know that well enough; but my business is to draw what I see, and not what I know is there.'" This is doubtless true enough, but its chief application in Ruskin's mind had reference to the science of anatomy, the study of which, he thought, had spoilt many a good artist by giving him the "butcher's view." It can scarcely, however, be applicable to Light, for that artist has yet to arise who is so imbued with optical theories as to distinguish blue from red by drawing ether waves

of the different lengths that science postulates. Probably the repulsion of the artist to the science of light is due, at least in part, to the feeling that the splendor of light and color has little to do with the mechanical concepts of optical theory; but although modern science is accustomed to speak in the language of mechanics, it is quite prepared to admit that the artist's feeling may be entirely an affair of the spirit. It would like to see all artists walking in its ranks. Of course no one would seriously suggest that the study of optical science will make you an artist. If, however, you have the artistic spirit, you will understand that the science of Light is really a work of conscious and premeditated art. Your intelligence will urge you to know at least something about the subject, and you may even agree with Ruskin that "whatever it is really desirable and honorable to know, it is also desirable and honorable to know as *completely* as possible."

If you will permit me one word more of an introductory character, I should like to say that it will be my endeavor to present the subject with all possible simplicity. This, I hope, needs no apology; at any rate you will not suppose that I underrate your powers if I try to make things as easy as I can. Of course it is true, as Ruskin says, that "no study that is worth pursuing seriously can be pursued without effort"; but it is needless to make the effort painful merely for the sake of preserving our dignity. And while I shall avoid technicalities as much as possible for the sake of lucidity, for the sake of art I shall equally avoid any attempt at word-painting. The subject is too great in itself for anything but a studied simplicity in its treatment.

The theory of light has, in these latter days, achieved so many successes, and been worked up into so nearly

perfect a form, that there is a temptation to forget the labors of the great men of the past who have done so much to make these modern victories possible, and to present the theory in the form it bears to-day as if no other had been thought of. It is a temptation to be rigorously withstood. In science no less than in other branches of human activity we must not allow ourselves to forget that the roots of the present lie deep in the past. By so doing we neglect a valuable aid to the thorough understanding of the present, and we rob ourselves of the pleasure and the illumination that comes from tracing the development through the ages of a great idea. Unfortunately, in the present lectures we shall have no time for this, but we can scarcely avoid dipping a little into the past, even in the most cursory examination of optical theory.

Doubtless thoughtful men of various races must have pondered over the phenomena of light, but amongst the earliest references in literature to anything that can, by the utmost stretching of terms, be dignified by the name of a theory of light, are the speculations of some of the philosophers of Greece. The Greek mind is so often and so justly held up as an object of admiration that it is with something of a shock that we read the puerilities of its greatest thinkers when dealing with physical science. In the field of optics they seem mainly to have been occupied with the question whether objects become visible by means of something emitted by them, or by means of something that issues from the seeing eye. Five centuries B.C. Pythagoras and his school held that vision is caused by particles continually projected into the pupil of the eye; while later, Empedocles maintained that to excite the sense of sight there must be something emitted from the eye, and that this must

meet with something else proceeding from the object seen. Listen to and get what enlightenment you can from Plato's explanation of an act of vision: —

"The pure fire that is within us the gods made to flow through the eyes in a single smooth substance, at the same time compressing the center of the eye so as to retain all the denser element, and only to allow this to be sifted through pure. When, therefore, the light of day surrounds the stream of vision, then like falls upon like, and there is a union, and a body is formed by natural affinity, according to the direction of the eyes, wherever the light that falls from within meets that which comes from an external object. And, everything being affected by likeness, whatever touches and is touched by this stream of vision, their motions are diffused over the whole body, and reach the soul, producing that perception which we call sight. But when the external and kindred fire passes away in night, then the stream of vision is cut off; for, going forth to the unlike element, it is changed and extinguished, being no longer of one nature with the surrounding atmosphere, which is now deprived of fire: the eye no longer sees, and we go to sleep; for when the eyelids are closed, which the gods invented as the preservation of the sight, they keep in the eternal fire." So much for his explanation of vision. Hear next his theory of colors. "There is a class of sensible things called by the general name of colors. They are a flame that emanates from all bodies, a flame that has particles corresponding to the sense of sight. Of the particles coming from other bodies that fall upon the sight, some are less, some are greater, and some are equal to the parts of the sight itself. Those that are equal are imperceptible, or transparent, as we call them, whereas the smaller dilate, the larger contract

the sight, having a power akin to that of hot and cold bodies on the flesh, or of astringent bodies on the tongue. Those that dilate the visual ray we term white, the others black." Aristotle, of course, objected to this as to most of Plato's science. He came, in a vague way, nearer to the modern view, as he regarded light not as material at all, but as the influence of a medium on the eye. He says: "Vision is the result of some impression made upon the faculty of sense, an impression that must be due to the medium that intervenes. There exists something which is pellucid. Light is the action of this pellucid, and whenever this pellucidity is present only potentially, there darkness also is present. Light is neither fire nor substance, but only the presence of fire, or something like it, in that which is pellucid." This is, I think, the clearest account we have in Greek philosophy of the nature of light. I will not venture to say that it is obscure, but perhaps I may be permitted to use Aristotle's own phraseology, and suggest that "its pellucidity is present only potentially."

However, I must not weary you further with the speculations of Greek philosophers or medieval thinkers. It is not until the seventeenth century of our era that we get any really great advance, when Snell discovered the law of refraction and Newton made his classical experiments on color. We may well pause just for a moment to consider why in all those ages the world of science stood so still. Certainly it was not due to any lack of intellect. No one who looks into the matter can fail to recognize that there really were giants of old. Indeed it would be a hazardous thing to assert that within the last two thousand years there is any evidence of human advancement, if you measure man merely by the intellectual power of the greatest of his kind.

Talk with an ancient or medieval philosopher on matters of science, and he appears like a child; but take him on his own ground, and you will have to wrestle hard indeed to overthrow him. No, it is not in *mind* but in *method* that the race has advanced; and where we are superior to our forefathers is in the fact that we have learned — at any rate in science — first to lay a solid foundation of fact before we begin to theorize.

If you search in the field of optics, you will find that the only general facts known before the seventeenth century could all be stated in a few minutes. They were these: —

(1) Light travels in straight lines — a partial truth that proved to be more misleading than a lie. (2) The fact and the law of reflection. (3) The fact of refraction — not its law. (4) The fact of total reflection. These things are probably familiar to most of you; but for the sake of those to whom they are not, it may be well to direct your attention to a few simple experiments, so that all may realize clearly how much and how little was known in the good old days. In the first place, "light appears to move in straight lines." This is familiar to every one who has looked at a shadow and noticed that its contour is determined by drawing *straight* lines from the source of light past the edges of the object that casts the shadow. The light goes straight past the edge and does not bend round corners, so that we are tempted to lay down the law that "light moves in straight lines." The one objection is that it is not true. As we shall see later, this is a case in which we are misled by our senses. Light *does* bend round corners, but under ordinary circumstances the bending is so slight that the eye is unable to detect it. So much for one of the four general principles known before the seventeenth century. Th

other three can all be demonstrated by slight modifications of the same experiment. Darken your room as much as possible, and let light from the sun stream in through a single chink. (If you prefer to work at night, you can make an artificial light take the place of the sun.) Let this light fall on a tumbler of water in which are two or three drops of milk. Blow in a little smoke to show the path of the ray, or scatter a little powder, if you object to smoke. You will observe that the ray, when it strikes the surface of the water, is *bent* back into the air. This is the *fact of reflection.* Its *law* is that the incident and reflected rays are equally inclined to the surface of the water, and this also you can verify. If you are interested only in reflection, it will be better to use an ordinary mirror rather than the water to produce reflection, as thereby you will get more light reflected, and will have less difficulty in seeing the reflected beam distinctly. The advantage of the water is that it enables you to observe the other phenomena, to which reference has been made. You will see that not all the light is reflected, but that there is a bright beam in the water. This beam is not in the same direction as the incident one; it looks as if the beam were *broken* at the surface. This is the *fact* of *refraction;* the law that enables us to predict exactly how much it will be broken was not yet known at the time of which I speak. In this experiment you have allowed the light to strike the water from above. By means of a reflecting mirror it is easy to make it reach the water surface from below. If you do this, you will again get the phenomena of reflection and refraction; but as you vary the angle at which the ray strikes the surface, you will come to a region where the refracted ray disappears. *All* the light is then reflected. This is the

phenomenon of *total reflection*, and here again the fact, but not the law, was known before the seventeenth century. Before making these experiments, it may be well to look at Fig. 1, which indicates what is to be expected.

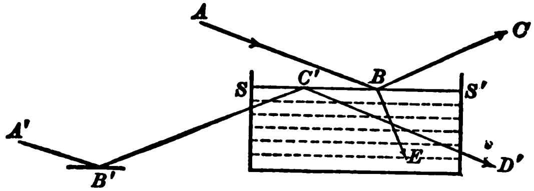


FIG. 1

The line SBS' represents a section of the surface of the water in the glass tank that stands upon this table. AB is a beam of light from the lantern, and when this strikes the water at B, part of it is reflected along BC and part refracted along BE. The line $A'B'C'D'$ represents the path of the beam when things are arranged to exhibit the phenomenon of total reflection. A beam $A'B'$ from the lantern is reflected along $B'C'$ by a plane mirror at B'. When the angle at which it strikes the water surface SS' is properly chosen, the whole of the light is reflected along $C'D'$.

I will now ask Mr. Farwell to show you these experiments, not because they are novel or beautiful, but partly because they deal with fundamental facts, and partly because I want to bring home to you the striking fact that the results of human thinking over the phenomena of light for thousands of years before the seventeenth century of our era can all be presented in a single minute. How little these thinkers really knew! To those of you who are familiar with the immense field of modern optics, the omis-

sions will appear enormous. The one that I wish to emphasize to-night is the absence of any exact knowledge and any feasible theory of color. Its absence is the more striking, as color is an attribute of light that impresses not only the artist and the man of science, but every normal human being. The man who unlocked this secret was he who is everywhere hailed as the greatest of all physicists, the man whose achievements so changed the current of men's thoughts as to form the Great Divide, in the realm of science, between the ancient and the modern world — Isaac Newton. You know that his greatest achievements were in other fields, yet even in the domain of optics I must to-night confine myself to a very small portion of what he did, but that portion was epoch-making.

I hold in my hand his little book on "Opticks." Turn over its pages, and you will be struck by the style. The writer has evidently been brought up in the strict school of the geometers, with Euclid for his model. Here is no collection of obscure musings and hazy speculations, but clear statements of what is to be proved and the manner of proving it. After some preliminary definitions, the book proceeds thus: —

"Proposition I. Theorem I. Light which differs in color differs also in degrees of Refrangibility." Then follows the proof. "Prop. II. Theor. II. The light of the Sun consists of Rays differently Refrangible." And so on. Notice most carefully that he does not tread the old high *a priori* road. He is not content, like many a philosopher before and since, to sit in an obscure study and think. He also observes. Listen to the first sentence of his book. "My design in this book is not to explain the properties of light by hypotheses, but to propose and prove

them by *reason and experiments*." That is the combination that tells — reason and experiment. Neither is of much use without the other. We have seen where reason alone landed the greatest thinkers of the ancient world, and experiment alone would have been equally futile. To advance science by experiment is no haphazard process, as some imagine. It is a supreme effort of the mind, requiring imagination and a working hypothesis to make it effective. Without this the experimenter does not know what questions to put to Nature. Compare a skilful cross-examiner in the law courts with a novice. The latter asks questions at random, in the hope (generally a vain one) that he may hit on something relevant. The former has a theory and a consequent method.

The experiments that Newton describes to prove his various propositions are very numerous. As time is short, we must to-night select a very few. Those of you who are really interested will doubtless repeat most of Newton's experiments for yourselves. I expect that you could buy the necessary outfit at one of those marvels of New York — a ten-cent shop. The apparatus is certainly wonderfully simple, consisting usually of little more than a glass prism, and this fact may suggest the query why, in this wiser age, such costly machinery is required to produce much less epoch-making results. The answer is that, by the labors of men like Newton and their followers, science has advanced so rapidly and has become so much more exact that instruments of precision, generally costly, are needed to move forward where rougher tools would have availed before. Newton's first proposition is that "Lights that differ in color differ also in degrees of refrangibility." The *fact* of refraction has already been brought before you. You have seen that

when a ray of light goes from air into water or glass, the ray is bent. Newton states that the amount of bending depends on the color of the incident ray. His proof, as usual, is by experiments. The first one is as follows: Taking a piece of paper, he draws a straight line across the middle and paints one half of the paper a bright red and the other a vivid blue. The paper is laid on a table before a window and viewed through a prism of glass held with its edges horizontal. If the wedge-shaped part of the prism is held upwards, the paper appears to be lifted upwards; but the two halves are not lifted equally, the blue being raised much more than the red. He concludes that blue light is more refrangible than red, and by varying the colors it is easy to extend the observations so as to convince yourself that color and refrangibility are intimately related. Mr. Farwell will show you this, with the modifications required by the facts that he is working at night, while Newton used sunlight, and his experiment must be seen by a large audience and not by a single observer. The second proposition of Newton is that "The Light of the Sun consists of rays differently refrangible." The proof by experiment was made by darkening a room and making a small circular hole in the window shutter, through which the light could stream. This light, falling on some white paper on the opposite wall, produced a light circular spot quite free from color. He then interposed a glass prism in the path of the sunlight, and looking at the paper on the wall, found, instead of a circular colorless spot, a brilliant display of color — what he called a spectrum — no longer round, but about five times longer than it was broad. The fact that it was not round proved the falsity of the current rules of "Vulgar Opticks," as he

called them. The arrangement of the colors in the spectrum showed a difference of refrangibility in agreement with his first proposition; whilst the presence of so many colors indicated what a highly complex mixture sunlight really is. Mr. Farwell will repeat the experiment.

This proposition of Newton, which sets out the composite character of sunlight, is his most important one. If you really grasp it, you are on the way to understand most of the phenomena of color. It establishes the paradox that you produce color by suppressing it. With all possible colors mixed, you have colorless sunlight; take out one or more of its elements, and color is the result. Newton, of course, realized the importance of his proposition, and so he set himself, even more rigorously than usual, to establish the principle that he thus enunciates, "The Sun's light is an heterogeneous mixture of rays, some of which are constantly more refrangible than others." He changes the conditions of his experiments in various ways, subjects the sunlight now to reflection and now to refraction, in some cases from natural bodies, in others from those artificially constructe — in all cases the results agree in establishing his mai contention. There is no time to describe these differe devices — a single variant from that already shown mu suffice. We have seen that a ray of light in water or gla will as a rule be partially reflected and partially refracte when it comes to the surface separating the water or gla from air. However, at a certain angle of incidence, an ang that is called the *critical angle*, there will be no refractio and the light will be totally reflected. Now Newton sa that if different colored rays were differently refrangible, t critical angle would be different for each, and consequen that if sunlight were composite, the phenomenon of to

reflection would occur at different incidences for the different constituents. To test this, he took two similar right-angled prisms of glass and held them together, but not quite in optical contact, so that their cross-section formed a square. Under most circumstances the light from the sun falling perpendicularly on such an arrangement would pass through without change. Owing, however, to the film of air separating the two prisms, the angle of incidence at this separating surface might lie, for any color, within the range of total reflection. Such a color could not get through the double prism, being totally reflected at the common boundary of the two prisms. Thus, in the beam that emerged, some of the color would be suppressed, and the light would no longer be white like sunlight. To test its exact character, the emergent beam had to be analyzed, and the simplest instrument for this purpose is a prism which separates the different constituents by refracting them all differently. Newton therefore placed a prism behind his double prism, and watched what happened as the latter was slowly turned round so as to change the angle of incidence on the air-space between the two right-angled prisms. He found that just when the film of air met the rays from the sun at the critical angle for blue, the blue disappeared from the spectrum produced by his last prism, and that as the revolution was continued, all the colors disappeared in succession, as the critical angle for each was reached. This I shall now ask Mr. Farwell to show you. The arrangement of the apparatus is indicated in Fig. 2.

P_1 and P_2 are the right-angled prisms referred to. A strip of tissue paper keeps them from actual contact, and they are held together by an elastic band. The light from

the electric lantern is focussed so as to fall as a parallel beam AB on the layer of air between the prisms, and if it fall at the right angle, the corresponding ray will be totally reflected along BC, and so will not enter the second prism, P_2. L is merely a focussing lens, P_3 is the analyzing prism, and S_1S_2 the screen on which the phenomena are observed.

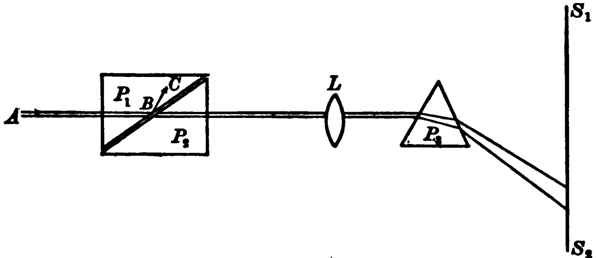


FIG. 2

Thus far I have dealt with only two of Newton's propositions. Of the many others that he lays down I can refer to but a few. Proposition V: "Homogeneal light is refracted regularly without any dilatation, splitting, or scattering of the rays." We have seen that when a beam of sunlight traverses a prism, its different constituents are differently refracted, so that, instead of a narrow, colorless band, we see a broad one brilliantly colored, and instead of a white, circular spot representing the sun, we have a long-drawn-out image with all the colors of the rainbow. The "explanation" of this phenomenon current in Newton's day was that the prism had the power of shattering the rays, an "explanation" typical of medieval science, which was generally satisfied with a mere name. Newton sounded the death-knell of this theory by showing that if the light employed were pure,—"homogeneal" was his phrase,—or

it were red, or green, or blue, and not a mixture of different colors, then there was none of this spreading out of an image, or dispersion, as we call it, so that the prism could not be endowed with any mystic power of shattering a ray. His method of proving this was as follows: He allowed a ray of sunlight to stream into a darkened room. This he

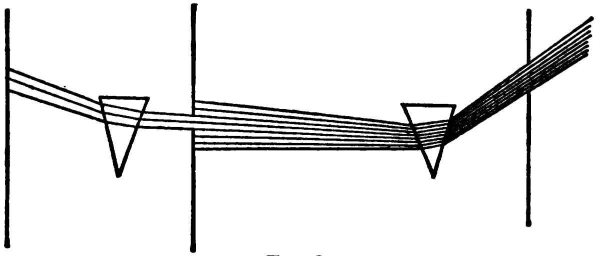


FIG. 3

intercepted with a prism, and so produced a spectrum with all the colors on a wooden screen behind the prism. This screen was pierced with a hole that allowed light to stream through and fall on a parallel screen behind it. The second screen also contained a hole, and by turning the prism round, Newton could sift out light from any part of the spectrum, and arrange that the light going through the two holes in the screens should be approximately homogeneous. He then allowed this homogeneous light to pass through a prism and make an image on a screen behind it. He found that there was no appreciable spreading out or dispersion of the homogeneous beam. Mr. Farwell will show this to you, and Fig. 3 will serve to give you a picture of the arrangement of Newton's apparatus.

Another experiment devised to serve the same end, and one that you can very easily try for yourselves, is thus

described by Newton: "In the homogeneal light I placed flies, and such like minute objects, and viewing them through a prism, I saw their parts as distinctly defined as if I had viewed them with the naked eye. The same objects placed in the sun's unrefracted heterogeneal light, which was white, I viewed also through a prism, and saw them most confusedly defined, so that I could not distinguish their smaller parts from one another."

In the second part of the first book of "Opticks," his second proposition is as follows: "All homogeneal light has its own proper color, answering to its degree of refrangibility, and that color cannot be changed by reflection and refraction." He proved by experiment that "if any part of red light was refracted, it remained totally of the same red color as before. No orange, no yellow, no green or blue, no other new color, was produced by refraction." And as these colors were not changeable by refraction, so neither were they by reflection. For all white, gray, red, yellow, green, blue, or violet bodies, such as paper, ashes, red lead, indigo, gold, silver, copper, grass, violets, peacocks' feathers and such like, in red homogeneal light appear totally red, in blue light totally blue, in green light totally green, and so of other colors. "From all which," he concludes, "it is manifest that if the sun's light consisted of but one sort of rays, there would be but one color in the whole world, nor would it be possible to produce any new color by reflections and refractions, and by consequence that the variety of colors depends upon the composition of light."

Time will not permit me to do more than mention two other important propositions of this book. Proposition IV: "Colors may be produced by composition that shall be like to the colors of homogeneal light as to the appearan

of color, but not as to its immutability." Proposition V: "Whiteness and all gray colors between white and black may be compounded of colors, and the whiteness of the sun's light is compounded of all the primary colors mixed in a due proportion."

Having unlocked these secrets of Nature, he applies the principles thus established to explain the colors made by prisms, the colors of the rainbow, and the permanent colors of natural bodies. And he shows generally that "if the reason of any color whatever be required, we have nothing else to do than consider how the rays in the sun's light have, by reflections or refractions, or other causes, been parted from one another or mixed together."

Unless you know something of modern physics, you will not realize the full significance of Newton's conclusions, but I hope you will see that, having regard to all that had gone before, they were epoch-making. By the aid of so cheap an instrument as a prism, but with a priceless mind, Newton revealed the true nature of color. Those of you who have visited the English University of Cambridge, have probably been in the Ante-Chapel of Trinity College, and if you had any knowledge of science, you must have looked with interest, if not with admiration, on a marble statue of Newton standing pensively with a prism in his hand. Long after Newton's day there came as an undergraduate to the same old university the poet Wordsworth, and he tells us how, looking from his rooms in a neighboring college, he could behold—

"The antechapel where the statue stood
Of Newton with his prism and silent face,
The marble index of a mind forever
Voyaging through strange seas of Thought, alone."

What epoch-making voyages were his! The one that we have dwelt upon to-night would have been enough to make the reputations of a score of men, but as you are doubtless aware, it is one of the smallest of his achievements. His contributions to mechanics, celestial and terrestrial, and his introduction of the greatest engine of advancement in scientific investigation (the calculus) far outweigh in most men's minds what he did for optics. We need not attempt to estimate the relative values of these various products of his genius. It is enough to recognize him, as does the whole scientific world, as the greatest man of science that has yet appeared. The impression that he makes on the minds of all who have the capacity to understand him is of a being almost superhuman. You feel that you are in the presence of no ordinary master. All seems so great, and yet done so simply and without apparent effort. How came these mighty powers to such a man? Is genius hereditary, and was Newton's thus acquired? His forebears were commonplace enough, and there was none of eminence within the immediate circle of his relatives, so that he seems a sport of Nature. What natural advantages did he have? Was he born rich as the world counts riches, or with the greater riches of a fine physique? His father was a mere yeoman and, at his birth, his mother a poor widow. He was a sickly infant, not expected to live for a week. What of his education? He went to an obscure school at Grantham, where I am sure they knew little of what are now the most approved methods of pedagogy, and afterwards to the University of Cambridge, where they cared less. Nature rarely seems to trouble much about the education of her favorite children, and after all that we can say, the wind of genius blows where it listeth.

Finally, what of his character? It comes as a shock to find a grave moral weakness in a great man. One thinks of Bacon and the cutting description of him, doubtless somewhat exaggerated, as "the greatest, wisest, *meanest* of mankind." Fortunately, amongst the leaders of modern physics, there has been no such unhappy combination. To speak only of the dead, such men as Faraday, Maxwell, Helmholtz, Fitzgerald, and Stokes were men whose moral dignity everywhere commanded respect. And I am glad to say that this was true of Newton in a preëminent degree. His was a nature of unusual dignity and calm, absolutely free from the petty ambitions of lesser minds, and modest to a degree. As an old man, worshiped by the intellect of Europe as the greatest of his race, these were his words: "I know not what the world will think of my labors, but to myself it seems that I have been but as a child playing on the sea-shore, now finding some pebble rather more polished, and now some shell rather more agreeably variegated than another, while the immense ocean of truth extended itself unexplored before me."

Just one word more. How often, when all else about a man is satisfactory, his mere look disappoints! On the screen is thrown a portrait of Newton, and in contemplation of that beautiful face perhaps I may appropriately leave you.

II

COLOR VISION AND COLOR PHOTOGRAPHY

As the arrangement of this course is not entirely haphazard, it is of some importance that at each lecture you should recall the main results reached in what has gone before. Apart from the simple laws of reflection and refraction, our chief concern in the last lecture was the phenomenon of color, and the most important conclusions were two: first, that there is an intimate relation between color and refrangibility; and second, that sunlight is not a simple thing, but a compound of numberless constituents. I would have you remember that all the results were based on experiments that you actually saw performed. Of course the facts are one thing, and the language in which you choose to describe them is another. Science has her own language, unfortunately a highly technical one in these latter days. I remember the regret expressed by a distinguished scholar of my own university for the good old days, when men of science could express themselves in a pleasing Latinity that every scholar could understand. The change is, for many reasons, to be deplored. I do not refer merely to the obvious loss that comes from the abandonment of a universal language, but rather to the [illegible] that ensue from the splitting up of scientific language by repeated specialization, so that a chemist no longer understands a physicist, and neither has anything but the fa[illegible] conception of what a botanist is talking about.

For good or evil, a physicist likes to make use of mechanical terms, and feels that, when he does so, he knows his own language and can express himself with precision. How, then, is he to describe the phenomena of light? He does it with the aid of terms that naturally suggest themselves when dealing with the familiar experience of *wave-motion.* Waves in some form or another we all know well, whether in air or water or the solid earth. When I speak, a wave of sound spreads into the room, and at every point where my voice is heard there is a to-and-fro motion of the air, a periodic disturbance, as it is called, that constitutes the essential feature of a wave-motion. At sea the wind disturbs the water and sets up a to-and-fro motion that rocks you and the ship in which you lie, gently or otherwise, in the cradle of the deep. Some great upheaval in the earth itself originates a to-and-fro motion which spreads as an earthquake wave around the globe with havoc in its trail. In all these cases you have a to-and-fro motion in a medium — the media being air, water, and the earth. According to modern physics, light is due to just such a to-and-fro motion — a wave, if you prefer the term — in a medium that we call the ether. This ether is an abstraction; that is, it is conceived of by abstracting or picking out certain qualities of air and earth and water, and refusing to abstract some others. Why should we perform this curious feat? Because it helps us to do wonders, to coördinate with simplicity and ease countless optical phenomena that no mind could otherwise grasp and no memory retain; while, without it, all seems chaos.

In the to-and-fro disturbance that we call wave-motion there are two elements of special importance: the magni-

tude of the disturbance, — *amplitude* is the technical term, — and the *frequency*.

Watch a cork floating on the smooth surface of the Hudson River, and then observe it bobbing up and down as a wave advances over it. The greatest height it rises is the amplitude, the number of times it moves upwards in a second is the frequency. On these two elements, amplitude and frequency, more than on anything else, will depend the damage that the wave does if it strikes a movable object. If the wave be very high, it will have great capacity for work, useful or destructive; under such circumstances, it is said to be of great intensity. But what it effects will also depend very largely on the frequency. I shall have to emphasize this so much in the next lecture that now I need do no more than state the fact.

I have said that, according to modern theories, light is to be regarded as due to waves in the ether. The effect of these, as of any other waves, will depend on what they strike. Light, of course, may shine on a stone, but the stone will certainly not see light. Hence, if we are to understand the phenomena of light, we must know something of the mechanism, the eye, that receives the impress of the ether waves. According to our theory, the waves in the ether beat upon the eye in much the same way that waves in the sea dash themselves on a rock-bound coast. The analogy, however, would be closer and more instructive if we took the case of waves dashing on something that is itself movable. Think of the waves striking a ship at sea; their effect depends mainly on their height and on their frequency. So it is with waves of light beating against the eye. Great height corresponds to great intensity, a brilliant light; frequency is the clue to *color*. If the ether waves

strike on a *normal* eye 450 million million times per second, then no matter what their intensity, they produce the sensation of *red;* if 550 million million times per second, they produce the sensation of *green;* if 600 million million times per second, the sensation of *blue.* If the eye be abnormal, the color sensation may be quite different.

At this stage the interesting and important question arises: Can the sensation of blue (or similarly of any other color) be produced in any other way than by the regular impact of ether waves striking the eye, and setting up periodic disturbances therein, at the rate of 600 million million per second? The answer is that it can. Newton knew this, and stated it in one of his propositions quoted in the last lecture, and long before Newton's time the artists had learned it from experience. To paint, it is not necessary to have every color on your palette, for although it may be convenient to have quite a number, you can produce almost any effect by the proper mixture of a few. By pondering over these facts, a theory of *primary colors* was evolved, a primary color being one that cannot be formed by the mixture of any other colors. The artists, working with impure colors, decided that the primary colors were three — red, yellow, and blue; had they been able to effect a mixture of pure colors, they would have fixed on red and green and violet. This important fact is sometimes enunciated in an algebraic form, what is called a color equation, and may be thus expressed:—

$$\text{Any color} = aR + bG + cV,$$

provided the coefficients a, b, c be properly chosen.

It may interest and amuse you to test this statement for yourselves. Nothing but the simplest apparatus is

required, — a common top, a stiff piece of paper, and pigments that give the three colors, red, green, and violet. Cut out a circular disk from your paper and divide it into sectors by drawing lines from the center. Paint three sectors with the three different colors, place the disk on the top, and spin it. As it spins, you will perceive a definite color due to the mixture of the three in the proportions that you have chosen, and by varying those proportions (*i.e.* by altering the size of the sectors), you will learn to produce any color that you may desire.

Before proceeding farther, I wish to impress on you the fact that I am not now presenting any *theory*, but merely stating certain facts of observation. All the colors that we know can be produced by suitable mixtures of these three, Red, Green, and Violet. This is the great, though certainly not the only, fact that any theory of color vision has to account for. These theories deal with the mechanism of the eye, and their object is to suggest a mode of working that will fit in with all the facts. Of various rival theories, only two are worth considering to-night. The first was clearly stated by Young, and afterwards developed by Maxwell and Helmholtz, all men of the first rank as physicists, so that their ideas naturally commend themselves to men trained in physical science. The other is more modern in its origin; it was suggested by Hering, and being couched in physiological language, finds more favor with the physiologists than with the physicists.

As far as the perception of color is concerned, it is agreed that the most important part of the eye is that inner wall, the retina, which is connected with the brain by the optic nerve. Close to this wall there is arranged a curious layer of what are known as rods and cones, some three millions

of the latter in an average eye. It is suggested that these rods and cones are the chief part of the mechanism which, when disturbed by an incoming ether wave, transmits the sensation of color to the brain. According to the Young-Helmholtz theory, these little cones can be separated into three classes, Red, Green and Violet, according to the sensation that they are capable of transmitting, or more accurately according to the color to which they are most sensitive. If, for convenience, we call them the R, G, and V cones, the V cone is most sensitive to violet, the G to green, and the R to red. It must be understood, however, that each cone is more or less sensitive throughout a considerable range of frequency. Perhaps it will tend to clearness if we represent the state of affairs on a diagram.

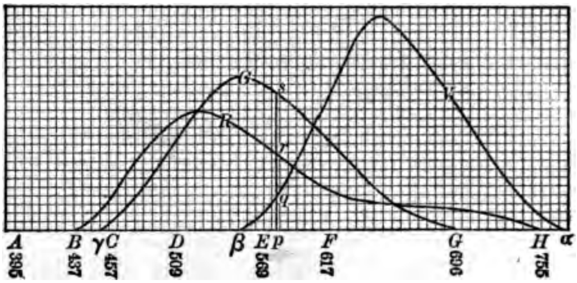


FIG. 4

The three curves in the figure show the sensitiveness of the R, G, and V cones when they are stimulated by waves of different frequencies. The frequencies are indicated by distances measured horizontally across the page and also by the numbers set out below the line *AH*. These are the number of *million million* vibrations in a single second, so that 395 at *A* indicates that, corresponding to this point in the

diagram, the incoming wave is oscillating to and fro 395 million million times each second.

The distances measured at right angles to the line AH indicate the corresponding sensitiveness of the three different cones, the scale being chosen so that when the three cones are equally stimulated, a sensation of white is produced. One very important fact indicated by this diagram is that the range of frequencies that stimulate the eye at all is finite. In the figure it extends from B to α, *i.e.* from 437 to 775 million million vibrations per second. There are many means of setting up vibrations having frequencies outside these limits, but they produce no sensation of light in a normal eye. However, the special purpose of the diagram is to indicate the relative sensitiveness of the different cones to a stimulus of given frequency. The V cones are sensitive only in the range $\alpha\beta$, that is, for frequencies lying between 775 and 550 million million, and are most sensitive when the frequency is about 650 million million. The G cones are sensitive from G to γ, when the frequencies lie between 696 and 450 million million, and are most affected when the frequency is about 550 million million. Lastly, the R cones are sensitive in the range H to B, where the frequency varies from 755 to 437 million million, and they are most violently affected when the incoming wave tosses the ether to and fro about 520 million million times per second. Just one more point before we dismiss this diagram: the color anywhere in the spectrum may be regarded as made up of not more than two sensations, with a dash of white. You will see from the figure that it is only in the region Gβ that more than two of the cones are stimulated simultaneously. At any point of this region, such as p, if we draw the line $pqrs$, the

parts *qr* and *qs* show that the R and G cones are stimulated so as to give the sensation of red and green, while the part *pq* shows that, to this extent, all three, R, G, and V, are *equally* stimulated, and this equal stimulation corresponds to the sensation of white. X

So far we have dealt only with the Young-Helmholtz theory of color vision. The rival theory of Hering is based on the observation that in most of the changes that take place in living subjects, two main phases present themselves. In the first, we have a *constructive* phase, when an organism appears to be built up out of lower forms, while in the second a *destructive* process sets in that decomposes the organism into lower elements. Hering supposes that there exists in the retina a visual substance that has three different constituents. The first we may call the Red-green, the second the Yellow-blue, and the third the White-black constituent. When an ether wave falls on the Red-green substance, it may not affect it at all; but if it has the right frequency, it may set in motion the *constructive* machinery, and so give the sensation green; or, on the other hand, it may start the *destructive* process, and red will be seen. (Some find support for this theory from their experience that red is a tiring color to look at long, while green is not.) The same sort of thing may happen to the other constituents; for example, to the Yellow-blue one. A certain frequency may set up the process of *destruction*, and we have yellow; whereas a differently timed stimulus induces construction, and a sensation of blue is the result.

We shall not have time this evening to enter into a comparison of the merits and demerits of these rival theories. They must be tested, of course, by their correspondence with the facts of experience. As far as the few facts hitherto

marshalled are concerned, either theory would do, as in fact would almost any other that suggested a mechanism sensitive to three or four different kinds of impressions. No such theory *explains* anything as far as color is concerned. The facts as to color are known; the object of the theory is to go from the known facts to the unknown mechanism of the eye that perceives. But although we have no time to discuss these theories further, we may perhaps just indicate the direction in which we must go if a decision as to their relative merits is to be reached. We must, of course, look at all the facts, but we should pay special attention to those that are likely to tell us most about the mechanism of the eye. You will have observed that it is generally when a machine goes wrong that you begin really to understand how it works or should work. When all is running smoothly, you sit comfortably in your automobile and care little how it works. There is nothing to think about except, perhaps, to decide by the mere turn of a handle whether a humble pedestrian is to be your victim or not. Let, however, something go wrong that brings you to your proper position under the machine; then you begin to really *know* its mechanism. So it is with most machines; the study of their defects and shortcomings is the surest road to a mastery of their working. Now the eye is not a perfect machine, and one of its defects, and by no means an uncommon one, produces color blindness. Some see no red, others no green, and a few no violet, whilst now and then a person is found who sees neither red nor violet. It is by the careful study of such abnormalities that we may best hope to test the merits and defects of any theory of color vision.

And now, as time is short, I must pass somewhat abruptly

to consider that other subject announced for discussion at this lecture — the subject of color photography. You will see at a glance that the two subjects of color vision and photography are not quite strangers to each other. It is obvious that the methods of giving to the eye the impression of the colors of a landscape must depend in some way, intimate or remote, on the mechanism of vision. At the same time it soon appears that we can progress with color photography without coming to a complete understanding as to the true theory of color vision. Whether we accept the Young-Helmholtz theory, or lean towards the rival one of Hering, or prefer some modification of either, will not much affect our grasp of the principles of color photography or our skill in its art. To understand these principles, the one thing needful is the full realization of the fact, already emphasized as crucial, that any color can be produced by a proper combination of a *finite* number of colors, for example, by a mixture of pure red and green and violet.

It is sometimes thought that color photography is a thing of yesterday; in reality it has occupied men's minds seriously for about seventy years. To trace the development throughout that period and to indicate the means adopted to overcome the countless difficulties that have arisen, would be a fascinating study of ingenuity and patience. For this, however, we have no time this evening, but must hasten to a brief description of a few of the more recent methods. The problem has been attacked in two totally distinct ways, which it is usual to distinguish by the adjectives *direct* and *indirect*. The aim of the direct method is to prepare a surface that is sensitive to light and that is so affected by the different colors that it reflects blue if it

has been touched by blue, red if it has been touched by red, and so for all the other colors. By far the most important step in this direction was taken in 1891 by Lippmann, although since then his process has been much improved by others. It would be impossible to explain the process intelligibly without some reference to the *Principle of Interference*, an optical principle of great importance that must be dealt with in a later lecture. Perhaps, then, it will be advisable to postpone any further reference to this method until the principle of interference has been discussed. I may say here, however, that up to the present no direct process has been so successful as the indirect, and that in this contest, as in others, it has been found that a flank movement is more effective than a frontal attack.

To those who know in any measure the immense debt that modern science, and particularly the science of light, owes to Maxwell, it is interesting to recall the fact that it was he that found the clue to the *indirect* method that in later days has proved so effective. As long ago as 1855, in a paper contributed to the Royal Society of Edinburgh, he wrote as follows: "Let it be required to ascertain the color of a landscape by means of impressions taken on a preparation equally sensitive to rays of every color. Let a plate of red glass be placed before the camera, and an impression taken. The positive of this will be transparent wherever the red light has been abundant in the landscape, and opaque where it has been wanting. Let it now be put in a magic lantern, along with the red glass, and a red picture will be thrown on the screen. Let this operation be repeated with a green and a violet glass, and by means of three magic lanterns let the three images be superposed on the screen. The color of any point on the screen will

depend on that of the corresponding point of the landscape, and by properly adjusting the intensities of the lights, etc., a complete copy of the landscape, as far as visible color is concerned, will be thrown on the screen." Here you have a clear indication of the path that will lead to the desired summit; but it is one thing to point out the way (a very useful thing, of course) and quite another to actually do the climbing. Difficulties of all sorts, some expected, others unlooked-for, may be encountered. Let us see something of the difficulties that have arisen in trying to follow Maxwell's directions.

Before attempting this, it may be well to recall to your minds the process of ordinary photography, now so familiar to everybody, and to describe it in the language of the modern theory of light. A photographic film or plate is coated with a substance, which, like every ordinary piece of matter is, according to the generally accepted theory, made of molecules — each molecule being a group of smaller parts, the atoms. When a wave of light beats upon such a plate, it shakes up the molecules more or less violently, and tends to shatter them to pieces. It does not destroy them; but, if its action be forceful enough, it so disturbs the atoms as to alter their relative positions and thus to constitute new groups or molecules. The new molecules have different chemical properties from the old, and the change is usually described by saying that a chemical action has taken place, or that light may affect things chemically. Whether any such action takes place depends chiefly on two things: the intensity and the frequency of the wave of light. A difficulty sometimes arises in the minds of thoughtful amateurs when they hear or read such statements as these. They emphasize the shortness of the exposure

required to affect a photographic plate, and ask how a little wave of light can do so much in one-tenth or one-hundredth of a second. To understand this, you must bear in mind the enormously high frequencies of a wave of light. The frequency depends upon the color, but we have seen that in round numbers and within the visible spectrum it lies between 400 and 800 million million. Imagine that you are watching a log floating in the sea, and that it strikes against a pier as it rises and falls with the waves, say once in six seconds — a not unusual state of affairs. What length of time would correspond to the exposure of a photographic plate to violet light for one-tenth of a second? It is a simple question of arithmetic.

$$\frac{800 \times 10^{12}}{10} \text{ vibrations} = 8 \times 10^{13} \times 6 \text{ seconds}$$
$$= \frac{8 \times 10^{13} \times 6}{60 \times 60 \times 24 \times 365} \text{ years} = 2 \cdot 1 \times 10^{6} \text{ years,}$$

or more than two million years. The log might do something to the pier in that time, and so it is not altogether surprising that, in an exactly corresponding time, the light does something to the photographic plate.

Let us suppose, then, that light from the various points of a human face beat upon a photographic plate for one-tenth of a second. The light from different parts will have different intensities, as there will be gradations of light and shade. The more intense light will batter the molecules more violently than the feebler light, and so will produce greater chemical action, which will show itself by greater blackness. Thus the lighter the object the blacker will be its image on the plate. In this way is produced the familiar *negative*, the gradations of light and darkness in the face corresponding exactly to those of darkness and light in the negative,

and it is by the *gradation* of light and shade that the whole picture is presented to the eye. If now we place this negative in front of a paper that is sensitive to light, and allow the light to stream through the negative on to the paper, you realize at once that the blacker parts of the negative will let through less light than the lighter parts, and thus that the parts of the paper underneath very dark portions of the negative will scarcely be affected at all, while those below bright portions will be battered and blackened. In this manner is produced a *positive,* and the gradations of light and shade in this will correspond to those in the original object, and thus present a more or less perfect likeness. Of course some means must be employed to fix the negative and the positive, so that they will not be sensitive to light after exposure. It would be out of place to discuss such problems here; I am merely recalling to you the main features of what I hope is familiar ground. Now if you have had any experience, you will realize that there are many places where you may go wrong and that to produce a first-class photograph you must know with precision many things; *e.g.* how long to expose your negative, under what conditions and for what time to develop it, how best to fix it, and so with the positive. It is sometimes said that in producing a photograph there are only two operations, making the negative and the positive, but of course each of these is complex, and if you go wrong in any one of at least half a dozen different operations, you spoil the photograph. With color photography, as practised until very recently, the difficulty is just this, that there are so many operations requiring precision and skill, and consequently so many possibilities of marring the final result.

The fundamental idea of most processes in color photography is to obtain different photographs of the different colored parts of the object and superpose them. Watch a chromo-lithographer at work, and you will see him make a great many pictures. One represents the dark red portion of the object, another a different shade of red, then there may be several blues, and so on. When all these are superposed, we get a picture more or less like the original. If the color scheme is at all complex, many separate pictures must be made before they can be combined, so that if we applied the same principle to photography we might need 20 or 30 different photographs to unite into a single picture. Were this the case, the problem of color photography would be practically hopeless, as each photograph involves so many processes, each with its pitfalls. Owing, however, to the cardinal fact already emphasized, that *any* color can be made by a suitable mixture of a few, viz. Red and Green and Violet, the process is greatly simplified. At most, three separate photographs are needed; hence the term, *three-color photography.*

Even with this simplification the process is difficult enough. Many are the methods that have been suggested, but it will probably make for clearness if I describe in outline a single one, and as far as principles are concerned, to understand one is to understand all. It is convenient to separate three different steps in the process: (*A*) the analysis of the complex colored light into three constituents and the production of three corresponding negatives; (*B*) the making of three positives from these negatives; (*C*) the recomposition of the three colored elements so as to completely represent the original object.

(*A*) The analysis is done by means of light filters, as

arrangement either of colored liquid or of films of colored gelatine interposed between the object and the photographic plate. Thus, if a vessel containing red liquid be placed before the lens, all but the red rays will be filtered out, and only the red part of the picture will impress itself on the plate. We have now such a variety of coloring materials at our disposal that we can get a filter of almost any color that we want; but the exact filtering qualities of any substance are determined by other things than mere color, and these are things that the unaided eye is not competent to detect. After many thousands of experiments, an immense amount of knowledge has been garnered in this field. The light that shines through two liquids may appear of exactly the same color to the eye, but it may affect similar photographic plates differently in the two cases. However, different plates are differently sensitive to the *same* light, and it was the discovery that plates coated with different chemicals are differently affected by the light, that really made color photography possible. By this time we have learned how to prepare a plate *A*, that will be sensitive to light that comes through filter *a*, and be little affected by the light from filters *b*, *c*, and *d*, while plate *B* is sensitive to the light that filters through *b* and is not much influenced by the others, and so for all the series.

It must be noted, however, that we need to know not only that a plate is sensitive, but the character of its sensitiveness. How long are you to expose is an important question in ordinary photography, and it is peculiarly so in three-color work, for if you make the reds too deep, or the greens too faint, you will utterly mar the effect. Hence you must know with some precision the relative sensitive-

ness of the different plates employed in the process. Of course, having obtained the negatives, they must be developed and fixed as in ordinary photography.

So much for (*A*), the analysis of the light and the production of the negatives. Now turn to (*B*), the making of the three positives. Here the main point to bear in mind is that an almost perfect agreement between the three colored elements is essential. Color is so delicate a creature that the slightest discord will jar. Hence the sensitive paper used for obtaining the positives requires unusual care in its production and treatment. The paper must be as nearly as possible inextensible, and the sensitive film of uniform thickness. The positives may then be obtained from the negatives by the ordinary process, and thus three *colorless* images are formed, each made up of reliefs in gelatine. These films are then put into baths that give them respectively the three colors corresponding to the original analysis by the light filters. It should be noted that if, as in the process we are now describing, the three pictures are not placed side by side and composed into one by some optical device, but are merely superposed, and if further, as in this process, pigments are used to give the colors in the positives, then the light filters must not be red and green and violet, but rather red and yellow and blue. The difference arises from the fact, well known to every student of color, that you get a different effect by mixing lights and by superposing pigments of the same hues as the lights. If you mix lights, as in the process of stippling, you *add* one thing to another. Red and green and violet waves each strike upon the eye and produce a color sensation of definite quality, depending on the relative intensities of the different lights. If, on the other

hand, you mix pigments, you *subtract* one thing from another. Superpose violet on green and this on red. To estimate the resultant influence on the eye, you have to consider how much of the red is taken out by the green and how much more of these two is subtracted in the passage through the violet. The process is seen to be *subtractive*, and you would expect the result to be different from the *additive* one that takes place when lights are mixed. Experiment shows clearly that there *is* a difference, and it was because the artists used a subtractive and not an additive process that they concluded, as we have seen, that the primary colors are red and yellow and blue instead of red and green and violet.

The last phase (*C*) of the process has still to be referred to, the recomposition of the three elements of the final picture. This is done by superposing the three colored films obtained as already described. The process, however, is much less simple than it appears at first sight. When the three films are superposed, some defect in one or other of the monochromes is almost sure to be revealed: the red may be too intense or the violet too faint, or there may be local faults. It is therefore necessary to superpose the films provisionally in order that such defects may be revealed, and then to have resort to various expedients for removing the defects. When the best has been accomplished, the films must be very carefully placed on top of one another so as to fit as exactly as possible, and thus you have a color photograph mounted on glass or on paper, according as you wish to view it as a transparency or not.

You will have realized, no doubt, that a process such as that described requires no ordinary care and skill. Many of the operations can only be satisfactorily performed in

a physical laboratory, with the instruments of precision and the skill in using them that such a laboratory affords. Under such circumstances, color photography could never become a popular art. Recently, however, a process due to the brothers Lumière of Paris has come into vogue, and this is so much more easily carried out that it may yet become quite popular. It is no longer necessary for the photographer to concern himself with the complex problems that have just been referred to; most of these problems have been solved for him by the maker of the *autochrome* plate, as it is called. The user of the plate has little more to do than expose and develop it, as he would in the photography with which we are all familiar.

The materials employed are simple. The plate is carefully coated with a paste made from potato starch. The starch is composed of fine grains, and these are separated into three sets and dyed respectively red and green and violet — for the process, as we shall see, is essentially an additive one. When mixed together in equal proportions, the grains form a powder not quite white, but of an olive-gray tint. This powder is scattered on a glass plate on which is an adhesive, and the surplus powder removed until there is left only a single layer of starch grains — some four million to the square inch. This layer is coated with varnish, and when covered with a sensitive emulsion of the right kind, constitutes the autochrome plate.

How does such a contrivance enable us to reproduce the colors of a landscape? The explanation, after what has been said already, is simple enough. The starch grains act as light filters; we may say approximately that the red grains filter out all but red, the green all but green, and the violet all but violet. The red light from any part of the

landscape will filter through the red grains only and reach the sensitive emulsion behind the starch. If this emulsion be sensitive to red, it will be acted upon chemically, and there will be a *black* spot behind each red grain, through which the light has come. Suppose, then, that light were now to shine from behind the emulsion, it would be stopped by the black spots, and wherever red was present in the original there would be darkness on the plate. In other words, the blackened emulsion constitutes a *negative* of the red part of the landscape. This negative may be turned into a positive by processes similar to those employed in ordinary photography. Wash away the black spots and leave them colorless, so that there is now a clear space behind the red grains that were originally affected. If now light shines through from behind, we should have a *positive* of the red part of the picture. What is true of the red is true also of the green and violet, and as we have already seen that any color can be represented by suitable combinations of these three, we are in a position to understand why the autochrome plate can give us by a single exposure a perfect picture, however complex be the scheme of color.

One feature of the process may require some comment. As the three constituent colors, red and green and violet, are, in this process, necessarily taken together, the emulsion must be as nearly as possible equally sensitive to these three colors. You must know that this is certainly not the case with the plates you use in ordinary photography. Such plates are highly sensitive to violet, and scarcely sensitive at all to red and very little to green. The fact that they are insensitive to red enables you to carry on the development in a red light, and so to see clearly what you are doing. The Lumière emulsion is sensitive to red and

green about equally, but it is much more sensitive to violet. To overcome this difficulty, at least in part, a yellow screen is inserted in front of the plate. This cuts out some of the violet light, and by diminishing its intensity compensates in a measure for the plate's supersensitiveness to violet. With this device the plate is rendered approximately panchromatic. As it is sensitive to all colors, you must work with it only in complete darkness.

In a moment I shall show you a large collection of color photographs taken by various processes, amongst others by that just described. I owe them to the courtesy of a student of Columbia University, who has made a special study of the subject. Before showing these, however, a few further remarks with reference to the Lumières' latest process may not be out of place. (1) As it stands to-day, the process is useless except for transparencies. The starch paste is not quite transparent, and absorbs so much light that the picture, when viewed by reflection, appears almost black. (2) The process will not give us photographs on paper. (3) The plate that is exposed is the same that afterwards presents the colored transparency. Hence a separate exposure is required for each picture, and there can be no multiplication of the same photograph, as there is in ordinary photography. (4) The process does not as yet lend itself to the art of the retoucher, nor permit any liberties to be taken.

[A large collection of color photographs was here exhibited.]

After seeing such pictures as these, the question naturally arises, What are the relations of color photography at its best to art? Will it aid the art of painting, or is there any chance that it may seriously rival that art, and possibly

even supersede it? Before attempting any answer, we must remember that color photography is still in its infancy, and we must make reasonable allowance for the improvements that are sure to come in the future. But what are its outstanding defects to-day? Several are suggested, but the one most generally emphasized is that a color photograph is still somewhat hard and metallic, that it lacks the softness and the charm of a real work of art. Your view as to this must be largely a matter of taste, and perhaps it is the wisest course to accept the maxim *de gustibus non est disputandum.* Personally, I am inclined to doubt whether a color photograph is *necessarily* hard, although, of course, I admit that it often is so. If, however, this hardness really exists as a *necessity,* and not as a mere accident, it is not easy to see to what it is due. There can be no doubt that a color photograph is capable of giving a faithful reproduction of each *detail* of the original, and if this be so, why should not the whole be faithful, and thus as soft and charming as the original? The answer is that, *possibly,* the final result may be marred by an excessive faithfulness in detail. In looking at a landscape, the eye takes it in as a whole and not by separate parts. Every color is modified by the presence of all the others so that the actual appearance of a single leaf is somewhat different from what it would be were you to isolate the leaf and examine it alone. Now the photographic plate sees by isolating, and it presents the exact intensity of each constituent color as it is, unmodified by the presence of the rest. It may be the failure to allow for the subtle influences of neighboring colors that produces a sense of harshness and a consequent lack of charm. But, you object, the eye looks at the photograph as a whole, and why, then, should

not the colors in the photograph react on one another and produce the same effect as they do in the original? Perhaps they do for some, but it may not be so for every eye. We must remember that there is an important difference between the photograph and its original: the one is seen as a flat surface, the other in perspective. The artist may be able to surmount the consequent difficulties by taking liberties with the details of the color, while the photographic plate is fettered by being bound too closely to an absolute truth of detail.

However, even if this be so, and color photographs be thus doomed eternally to a certain harshness, there can, I think, be little doubt that some day they will form a serious rival to all but the highest art. Such art can never be endangered. It will always hold, unchallenged, the great field of imaginative painting that appeals so powerfully to the heart and mind, whilst in the realms of portraiture and landscape painting there must always be moods and phases that only a great artist can seize upon and express. This will be the work of the few, those greatest of our race who show us aspects of things that otherwise we should wholly miss, and delight us by expressing clearly what we only indistinctly feel.

III

DISPERSION AND ABSORPTION

In the first lecture of this course I showed you that it was possible within the compass of a single minute to summarize all the knowledge of optical principles gained by man from the dawn of his intelligence until Newton appeared in the seventeenth century of our era. One of the few general facts known in pre-Newtonian days was the fact of *Refraction*, the fact, namely, that a beam of light is bent in passing from one medium to another, as, for example, from air to water. By considering carefully the *amount* of bending, Newton was led, as we have seen, to a clear enunciation of the relation between refrangibility and color and to a revelation of the composite character of a beam of sunlight. The white beam is a coat of many colors, and each color is bent differently in crossing a refracting surface. Thus, when a parallel beam of sunlight strikes the water, the different elements are *spread out* in the water. This is the fact of *dispersion*. It has already been brought before your notice by experiments. Our object to-night is to scrutinize it somewhat more closely and try to gain a clue as to the reason of the spreading out — in other words, we seek a theory of dispersion. Before setting out in the search, it is well to look another fact in the face, at first sight a very different one, although a closer examination reveals a strong family likeness between the two. This is the

fact of *absorption*, and particularly the fact that a substance may be transparent for one kind of light and opaque for another — it may freely transmit blue and absorb most of the red. The explanation of this involves a theory of absorption, and it is with theories of absorption and dispersion that we are to deal exclusively in this lecture.

I have already stated that a modern physicist prefers to speak in the language of mechanics, so that it should cause no surprise that in dealing with absorption and dispersion we take certain mechanical principles as the basis of our theories. One of these principles is so important that I must state and illustrate it as fully as time will permit, for unless you grasp it firmly, you cannot hope to understand the theories that will be presented to you; whilst if you do understand it, at least the main outlines of these theories should be easily and clearly seen. Suppose that you have a system of bodies at rest, and that you disturb it slightly from its position of equilibrium. If that position be stable, the system will oscillate to and fro like a ship rocking on the ocean, with a definite frequency that depends entirely on the arrangement of the system and the forces that act upon it. This frequency, *i.e.* the number of oscillations per second, may be called the *natural frequency*, as it depends entirely on what happens when the system is allowed to move naturally, without any interference from without. Suppose, next, that by outside action you *force* an oscillatory motion on the system. The frequency of this outside action is entirely at your disposal; you can make it what you will, and may find it convenient to style it the *forced frequency*. Now the mechanical principle that I wish to emphasize is this: the *disturbance produced in a system depends on the frequency of the oscillation forced*

upon it, and is very much greater when there is coincidence, or nearly coincidence, between the forced and the natural frequencies than when this is not the case. Perhaps the most familiar illustration presents itself in the problem of giving a child a swing. You can scarcely have failed to observe that the magnitude of the swing depends very largely on how your pushes are timed. If you push at random, you will sometimes help the swing and sometimes retard it, and the work that you do will be much the most effective if you always push when the swing is in the same phase of its to-and-fro motion, *i.e.* if you arrange that the forced frequency should coincide with the natural one. Here is a simple device that will illustrate the same principle. It consists, as you see (Fig. 5), of two pendulums, *A* and *B*, fastened by strings to a not very rigid support, *CD*. By swinging either pendulum, you see that its natural frequency depends upon its length, that the frequencies of the two pendulums are the same when the lengths are the same, and that by varying the lengths you can get almost any frequency that you may want. Now suppose I set *A* in motion and swing it at right angles to the plane *ACD*, so that it does not get entangled with the other pendulum. As *A* moves to and fro, the pull in the string *AC* will set up a vibration in the support *CD*, and this will be communi-

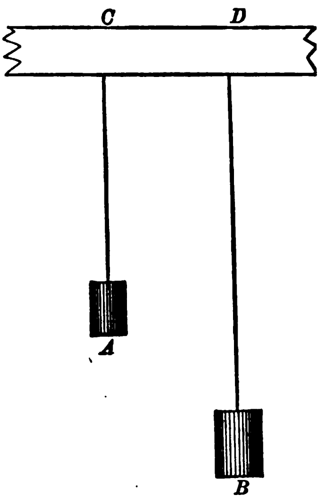


FIG. 5

cated to the string *BD*. When the lengths *AC* and *BD* are very different, you will observe that, in spite of the vibration communicated to *BD*, the pendulum *B* remains practically at rest; you see no signs of its motion. When, however, the lengths *AC* and *BD* are nearly equal, *B* begins to show signs of unrest, and it moves very perceptibly when the strings are equally long, *i.e.* when the forced and the natural frequencies coincide.

As another simple illustration of the same important principle, consider the motion of water in a bucket. If it be at rest to begin with, and you slightly disturb it, the water will oscillate backwards and forwards with a natural frequency that is easily observed. Now take the bucket by the handle and carry it off. As you step along regularly, each time that your foot goes down you will give a slight jerk to the handle of the bucket, and this will be communicated to the water. Thus forced oscillations will be set up, their frequency depending on the rate at which you walk. If, by design or by accident, you time your treads so that their frequency coincides with the natural frequency of the water, very much greater disturbance will take place than would otherwise be the case, and if the bucket be nearly full, a good deal of the water will flop over the edges.

Other illustrations might be drawn from various fields, for the principle is wonderfully far-reaching, and enters into the explanation of countless phenomena, from the trivial one just mentioned to some of the most stupendous and awe-inspiring catastrophes that human history records or the study of celestial mechanics reveals. To-night we have no time to enter further into the matter, except to bring before you one more simple experiment as a final illustration of the same underlying principle. *A* (Fig. 6)

is an organ-pipe, the end of which is closed by a thin film, formed by dipping the pipe into a soapy solution. If the air within the pipe be disturbed in any way, it will oscillate to and fro with a natural frequency that depends on the form and dimensions of the pipe. These oscillations will

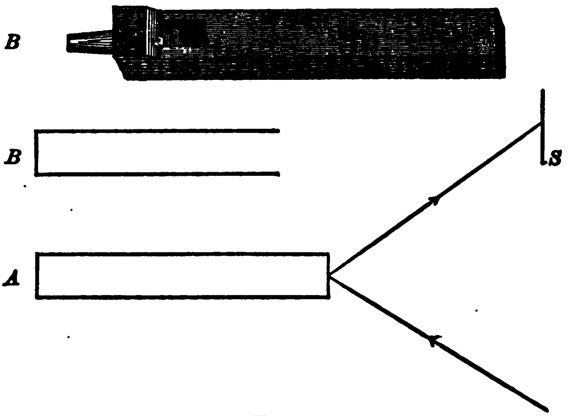


FIG. 6

cause the film to pulsate, and the character of these pulsations is revealed by allowing a beam of light to be reflected from the film on to a screen at *S*. By watching the movement on the screen, you can judge whether there is much throbbing of the film or not. Now let us force oscillations on pipe *A* by means of vibrations in another organ-pipe *B*, and vary the frequency of these vibrations by altering the length of this second pipe. You will observe that the disturbance revealed by looking at the screen is enormously more violent when the forced and natural frequencies coincide than when they are widely different. Here, as before, you see that for many purposes the magnitude of a shake is less important than its frequency, and that a small

vibration rightly timed may set up far more disturbance than a large one with a different frequency.

Bearing this principle in mind, imagine that you are watching a fleet of ships upon the ocean, and that, to begin with, all is calm. Then suppose that each is slightly disturbed, as by the shifting of machinery or cargo. Each ship will rock to and fro, with a natural frequency depending on the shape of the vessel and the arrangement of its cargo. If all the ships be similar, they will all rock with the same frequency. Now imagine a series of waves to come along and strike upon these moving ships.

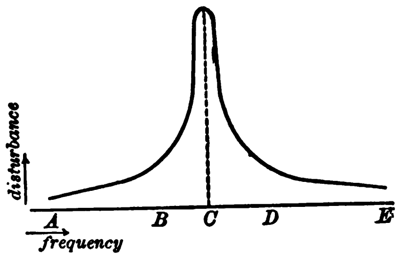


FIG. 7

They will continue to rock, and if the frequency of the incoming waves be very different from the natural frequency of the ships, there will be little change in the motion. Suppose, however, the frequency of the waves is gradually changed. As it approaches that of the natural frequency of the ships, the motion will be much more violent, and will be most marked when the natural and forced frequencies are the same. Once this stage is passed, and the forced frequency begins to differ largely from the natural one, the oscillations will die down, and in time you will return to calmness and to comfort. If you care to represent things graphically, you may indicate the forced frequencies by distances measured horizontally along the line *ABCDE* of Fig. 7, and the corresponding disturbances by lines drawn vertically. You then get a figure such as is here presented, where *C* corresponds to the natural frequency of the

ship's oscillation; and most of the disturbance is confined to a somewhat narrow range, *BD*, in the neighborhood of *C*.

In the region where the disturbance is considerable, the ships are rocking violently, and are therefore capable of doing a large amount of work. In technical language, they have great *energy*. This energy must come from somewhere, and its only possible source is the motion of the sea waves. Under these circumstances, a great deal of energy must be absorbed from the water waves, so that in the region beyond the ships you would observe a comparative calm. You have only to apply the same principles to the waves in the ether that give us the sensation of light to understand how a substance may absorb most of the light of one color, and be practically transparent to every other kind of light. In this case the ships are replaced by the atoms of matter, or rather, according to modern views, each atom is a whole fleet of ships. The old atom of chemistry is now replaced by a group of electrons, which move about like the stars in a cluster, and could they be seen, might appear as the Pleiades "glittering like a swarm of fireflies tangled in a silvery braid." If the ether waves have a frequency nearly coincident with the natural frequency of the electrons, they do so much work in disturbing these electrons that their energy is almost all spent. They have not enough left to stimulate the optic nerve, and we see no light. On the screen is thrown the familiar spectrum caused by sending a beam of white light through a transparent prism of glass. There is no appreciable absorption for any color; the spectrum is continuous, with every color of the rainbow represented. Now let the same light pass also through this chemical solution, and observe the change in the spectrum. A portion of the yellow is cut out and

replaced by absolute blackness, so that this kind of light is absorbed by the solution, while all other kinds come through just as before. Are we not justified in concluding, in view of all that has gone before, that the natural frequency of the electrons in the solution is the same as the frequency in the ether waves corresponding to this portion of the yellow?

In the case that we have considered, where there is a single moving object, such as a ship, there may be only one natural frequency, but with a more complex mechanism the natural frequencies may be many. If you regard the principal planets of the solar system as forming a single mechanism, each of the eight constituents goes through regular periodic movements with a definite frequency. Thus, in their motion round the Sun, they observe a strict and invariable law, Mercury taking 88 days (in round numbers), Venus 225, the Earth 365, and so on to Neptune, with the lengthy period of 60,127 days. Imagine, then, a mighty system of waves running across the solar system. If the frequency were such that the waves oscillated once in 88 days, most of the energy of the waves would be absorbed in dashing the planet Mercury to and fro, while the other planets would be comparatively little affected. If, however, the waves oscillated once in a year, our earth would be responsible for the absorption of energy, and similarly for other frequencies. Suppose, now, that the impinging waves had all possible frequencies. They would all pass through the solar system practically unmodified, except the eight with frequencies corresponding to the periodic movements of the planets. These eight would have their energy absorbed in disturbing the planets, and they would be relatively small and insignificant in the region of space

beyond the solar system. In exactly the same way will light be absorbed by a substance, those colors being cut out that correspond to frequencies identical with the various natural frequencies of the complex group of electrons composing the substance. In Fig. 8 you will see how many dark bands there are in the spectra of some simple substances, and if you realize that each of those dark lines

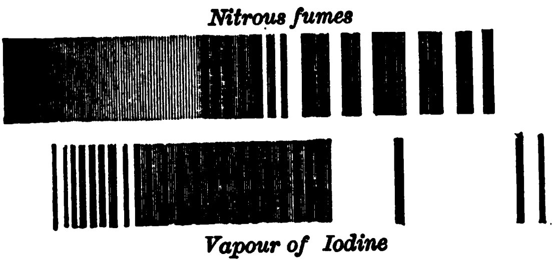


Fig. 8

indicates a different natural frequency, you will understand, in a measure, how complex must be the motions going on within the atom, and how formidable the task of the man of science who tries to master its mechanism.

Here you get a glimpse into a field of great interest and promise. The principle of fundamental importance is that the position of the absorption bands in the spectrum of any substance gives us information, and very definite information, as to the frequencies of the vibrations that go on within its atoms. If we knew the nature of those atoms, we could, were our mathematics sufficiently developed, calculate the frequencies of the vibrations. At present we are trying to reverse the process, and seek the unknown from the known, and the time may yet come when we can speak confidently of the minutest movements within the

atom. That time is certainly not yet, and probably for long we must devote ourselves with patient labor to accumulating facts that bear upon the problem. Much has already been done, and the positions of the absorption bands for many substances have been accurately observed over a wide range of frequencies. Let me call your attention to a few of the suggestive results that have thus been reached.

(1) The lines in the spectrum are not arranged at random, but according to laws which are more or less simple with different elements. The simplest case is that in which the relation between the frequencies corresponds exactly to the relation between a fundamental note and its harmonics. Strike the middle C of a piano, and you set up a to-and-fro motion in the air, there being 256 vibrations in a second, so that the frequency is 256. If you strike exactly an octave higher, you double the frequency. It is found that the lines in the spectra of some substances are arranged so that the frequency corresponding to one line is exactly double that of the other. If, however, you take all the lines into consideration, the relation between them is much more complex. One of the best-known examples is afforded by the spectrum of hydrogen. In 1885 Balmer showed that the frequencies corresponding to the different lines were all given by the formula, frequency $= a\ (1-4/n^2)$, where a is a constant and n any integer greater than 2. At this time only 9 lines had been observed, but as the number was extended beyond 30, it was found that Balmer's law still fitted the observations admirably. Thus, hydrogen seemed to present a unique example of simplicity, all the lines in its spectrum being connected by the same simple law. However, the later speculations of other physicists, particularly Rydberg, Kayser, and Runge, made it seem

probable that other lines existed, although they had not yet been observed. This was confirmed in a striking way by Pickering in 1896, while examining the spectrum of a star that shows the hydrogen lines strongly. He found a new series of lines related to the old ones in just the way that had been anticipated.

(2) It is found that with several elements the lines in the spectrum are arranged in groups of twos or threes, forming doublets or triplets, as they are called, and that the difference in the frequencies of the two members of a doublet is the same for each group, with a similar law for triplets.

(3) Where the lines are not arranged in doublets or triplets, they often appear in two different series. There is a series of sharp lines connected by one law, and another series of diffuse lines connected by a different law.

(4) The regularity in the spectra of some elements, *e.g.* tin, lead, arsenic, antimony, bismuth, and platinum, consists in the recurrence of certain constant differences of frequency between the lines.

(5) In what are known as band spectra, when the fluted spectrum is resolved by higher dispersion into groups of fine lines, it is often found that the frequencies obey a very simple law. They form an arithmetical series, *i.e.* each frequency differs from its predecessor by a constant difference. On careful examination, it appears that the spectrum is made up by repetitions of similar groups of lines, and it seems probable that the number and distribution of the lines in each group depend on the number and distribution of the atoms, or of the electrons that compose these atoms.

(6) Lastly, various relations have been suggested between the atomic weights of different substances and their natural

frequencies. Kayser and Runge have concluded that in the case of elements of the same chemical family which show a series of doublets in their spectra, the constant difference of frequencies between the two members of the doublets is very nearly proportional to the squares of the atomic weights. Marshall Watts has shown that with the class of elements that contains mercury, cadmium, and zinc, the ratio of the difference between the frequencies of certain lines of one element to the difference between the frequencies of the corresponding lines of the other element is the same as the ratio of the squares of their atomic weights. Morse, of Columbia University, has found that if you take a series of carbonates with different chemical bases — carbonates of magnesium, of calcium, of iron, of zinc, and so on, you discover a very simple relation between the atomic weight of the base and the frequency that is determined from the position of the absorption band, and that there is a similar law for the nitrates and the sulphates of the different bases.

These various facts that have been marshalled are, as I have said, highly suggestive, and they will inevitably be made the basis of many future speculations as to the nature of the atom. One thing at least they show us very clearly, namely, that in the little kingdom of an atom, just as in the mighty realm of the Sun, law is supreme. In many cases we have found the law, but there is much yet to be done to fit it into our other knowledge. At present we have only glimpses as to how this may be accomplished; but we see enough to give us hope that somewhere in the future the foundations of a new chemistry will be firmly laid. Then we shall know the movements of the atoms and the laws that govern them as definitely as now we know the orbits of the planets and the forces that confine them there.

Having delayed so long over absorption, I must hurry on to deal with dispersion, the theory of which I undertook to discuss at the beginning of this lecture. One aspect of that theory is simple enough: it is the aspect usually presented exclusively in elementary text-books on light. They tell us that dispersion is due to the fact that *where there is no matter present*, waves of light all move with the *same* speed, whatever be their frequency (or color), but that they move with *different* speeds in any *material* such as glass or water. This is true and very important, but it is no explanation. It does not go deep enough, for we want to know *why* these facts should be as stated. Before entering upon this, however, it will be well to see clearly that the fact of different speeds for different frequencies necessarily leads to dispersion. A simple analogy may help you to understand the phenomena. Suppose that you watch a column of soldiers marching steadily at the rate of 4 miles an hour, and that when they cross a certain line they come upon ground that is so much rougher that they advance at the rate of only 3 miles an hour. What would be the effect of this on an observer looking from a distance, and fixing his attention on the front of the column? Let ST in Fig. 9 represent the line that divides the smooth from the rough ground, and E, F, G, H, and similar letters, the positions of different soldiers at different times. If the front of the column was at $E_0\,F_0\,G_0\,H_0$ at any time, then an hour later it would be at $EFGH$, where $E_0\,E$ is 4 miles. An hour later than this H would be at H_1 (4 miles from H), but E would have covered only 3 miles on the rougher ground, and would be at E_1 where EE_1 is 3 miles. F and G would be at F_1, and G_1, as shown in the figure, having walked partly over smooth and partly

over rough ground. The front of the column would be represented by the line E_1, F_1, G_1, H_1. This is not parallel to $EFGH$, so that the column would have *changed its front*, and instead of moving in the direction EE_1, it would appear to be making along the direction ER, where ER is at right

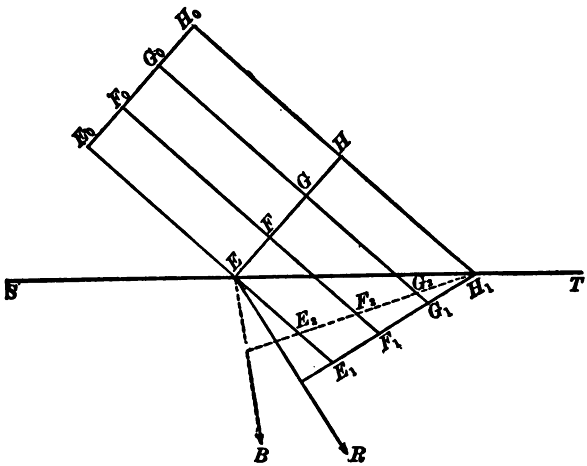


Fig. 9

angles to the front. If then you were describing the direction in which the column was tending, you might say that this direction was *broken* or *refracted* in crossing the line ST. It is not difficult, but I have no time for this now, to show that a similar result would be looked for with a ray of light on the theory of wave-motion. I trust that you can supply this step in the argument, and convince yourselves of the fact that refraction is at once accounted for by a change of velocity on crossing from one medium into the other. The step to dispersion is immediate and obvious. The amount that the column changes its front depends, as

you see, on the speed with which the men walk on crossing the boundary line ST. If they meet with even rougher ground than before, so that they move more slowly, the change of front will be greater than before. Thus, suppose that the column is composed of two sets of men, one in blue and the other in red uniforms, and that until they reach the rough ground they advance together at the same rate. (This corresponds to the fact that in free space, where there is no matter, waves of light of all colors have the same velocity.) After crossing the line ST, let the red men walk at 3 and the blue at 2 miles per hour. The latter will separate from the former, and will form a new column, whose front is in the direction $E_2 F_2 G_2 H_1$, in the figure, and which therefore appears to be moving in the direction EB. The columns will *disperse* in different directions, ER and EB, and if you apply similar reasoning to the case of waves of light, you will understand how dispersion is accounted for, provided only you can see that waves of different frequencies may have different speeds in the same medium.

This dependence of the speed of a wave on its frequency, on which we have just seen that any explanation of dispersion must be based, is no simple or obvious thing. It has occupied the minds of leading physicists for nearly a century and, in spite of all their labors, I am not sure that even now we thoroughly understand it. There is an initial difficulty that is very formidable. Think of a beam of light passing through water or a piece of glass. The water and the glass *look* thoroughly homogeneous, and even if you examine them with the most powerful microscope, you will get no direct evidence that one of the smallest parts differs in any essential way from another.

Now if waves of any kind are propagated in a homogeneous medium, it is difficult, if not quite impossible, to see how their speed can depend on their frequencies. However, we have to face the fact of dispersion, and this, if nothing else, would drive us to consider the possibility of matter, such as glass or water, being other than homogeneous. In its ultimate analysis we shall take it to be coarse-grained, and see how this will help us. The grains, or atoms, we shall regard as obstacles in the path of the waves affecting their progress. Some insight into the matter might be obtained by thinking of a column of soldiers marching through a forest; their rate of progress would obviously depend in some measure upon the distance between the trees. A far more instructive study for our purposes would be to observe carefully the rate at which waves were propagated in water in which floats are placed at regular intervals. If you do this, you will find that the speed of the wave depends upon its frequency, and that if you keep the floats always at the same distance, but modify the frequency, you alter the speed of the wave. This is just what you want for dispersion, and you may naturally think that you have found the key that unlocks the secret. So, no doubt, thought Cauchy when, early last century, he took up the problem and hit on this idea. But the way of the physicist is hard, and his lot is made peculiarly difficult by the duty that he has imposed upon himself of living up to a very high standard. He is not content with mere descriptive theories, he strives to state them in the strict language of mathematics and to obtain therefrom a formula. From such a formula definite numerical results can be calculated and a close and accurate comparison made between theory and observation. The object of a dispersion theory is to build

up from some rational basis a formula that will enable us to calculate the velocity of light for waves of different frequencies, and to obtain results that agree as closely as possible with what is derived from experiment. Instead of calculating the velocity directly, it is convenient for some purposes to estimate the ratio of the velocity of light-waves in free space to that of waves of the same frequency in the matter under consideration, *e.g.* glass. This ratio is called the *refractive index* of the matter, and we shall denote it by the symbol n. As light has the same velocity for all frequencies in free space, and this velocity is known, the velocity corresponding to any frequency in a material such as glass is at once obtained by dividing the known velocity in free space by the refractive index of the glass. The refractive index (n) will depend on the frequency (f), and any dispersion formula gives the relation that exists between n and f on the basis of the theory considered. Cauchy's theory led him to a dispersion formula of this kind:—

$$n^2 = K + af^2 + bf^4 + \dots$$

where $K, a, b, \dots$ are constants in any given material, but change if we pass from one material to another, as from glass to water. On putting this formula to the test of comparison with experimental results, Cauchy and his immediate followers found that it stood the test well, so that the problem of dispersion seemed to be solved. And yet to-day the position occupied by Cauchy has been wholly abandoned, and you may well ask why. I have time to touch on only three reasons to account for the fact that it has been necessary to look for some other theory of dispersion than the one that we are now discussing.

(1) In the first place, it must be noted that the observations were confined to a somewhat narrow range of frequencies. They were all in the neighborhood of the visible spectrum, the frequencies varying in round numbers from 400 to 800 million million. Such frequencies are specially interesting, from the fact that they alone produce in the human eye the sensation of light. But waves of other frequencies are easily set up and their influence detected. If their frequencies be high, they are specially active in affecting a photographic plate, while if low, they show themselves in the form of radiant heat. There is, of course, no reason why waves of such frequencies should be subject to any different law from that which holds for frequencies that give the sensation of light. Thanks to the patience and the ingenuity of modern physicists, we have by this time immensely extended the range of observation of refractive indices. In a few moments I shall refer you to such indices accurately observed for frequencies varying from about 13 million million to over 600 million million. Over such a wide range Cauchy's formula proves to be extremely ill adapted to represent the facts.

(2) The second objection to Cauchy's formula arises from a careful examination of his fundamental idea. That idea, as already stated, is that the velocity of a wave must be affected by the relation between its frequency and the distance between neighboring molecules. Assuming this, and noting the values of the constants in Cauchy's formula that are required to make it fit as well as possible with the observed facts, we can estimate approximately the distance between consecutive molecules in any substance. Now there are other and much surer ways of estimating these

distances, and it is found that Cauchy's formula separates the molecules far too widely. In a given length it would place only one where we have good reason for supposing that there are about thirty molecules.

(3) Thirdly, Cauchy's theory gives us no clue to the connection between absorption and dispersion, and these, from many points of view, we now see to be intimately related phenomena.

I have not time to do more than indicate the character of more modern theories of dispersion that endeavor to avoid these difficulties. The fundamental idea with them all is that the molecules, or, according to the more recent theories, the atoms, are complex structures, the parts of which can vibrate to and fro with definite natural frequencies. Thus in the group of electrons constituting an atom, each member may, under normal circumstances, move steadily in an orbit, like a planet round the Sun. When a wave strikes such a system, its speed will be affected just as in Cauchy's theory, mainly by two things: first, the displacement that the wave produces in the moving member; and second, the magnitude of the force that tends to restore that member to its orginial position. When dealing with absorption, we had reason to emphasize the fact that the displacement produced by the impinging wave would depend very largely on the relation between its frequency and the natural frequency of the moving system. Well-established dynamical principles lead us easily to a formula for the displacement corresponding to any given frequency, and the only matter about which we are in doubt is the character of the force that tends to restore a disturbed element to its original orbit. We find that if the frequency (f) is not very close to any of the natural

frequencies ($f_1 f_2 \cdots$) of the system, then the refractive index (n) should be given by the formula—

$$\frac{n^2-1}{n^2+a}=\frac{K-1}{K+a}+\frac{A_1 f^2}{f^2-f_1^2}+\frac{A_2 f^2}{f^2-f_2^2}\cdots$$

Here a, K, A_1, and A_2 are constants for any given material, the value of a depending on the nature of the intermolecular forces as to which we are, as yet, more or less in ignorance. The following table will show you how this formula fits in with the facts as observed in the case of rock-salt, a substance chosen because we know its refractive indices over an enormous range of frequencies. You will observe that throughout the whole range, theory and observation agree within the limits of experimental error.

It must be understood that the six constants A_1, A_2, f_1, f_2, a, K are determined so as to make the formula fit the facts for *six* arbitrarily chosen values of the frequency (f), and that the formula is tested by noting how close is its agreement with the remaining 60 observations, there being 66 of such observations in all. But there are other collateral tests. The constants f_1 and f_2, calculated, be it remembered, from observations of refractive indices alone, denote the natural frequencies of parts of the molecule. We have seen, in the discussion on absorption, that these frequencies determine the position of the absorption bands of the substance. Now the frequencies corresponding to the absorption bands can be determined by direct experiment, and it is found that they agree as closely as could be desired with the values calculated from the above formula. Again, if you look at the formula, you will observe that when the frequency is zero, so that $f = 0$, we have $n^2 = K$. If the frequency is zero, that means that there are no vibrations per

f (in million millions)	n (theory)	n (observation)	f (in million millions)	n (theory)	n (observation)
617	1.5533	1.5533	255	1.5303	1.5303
609	1.5526	1.5526	250	1.5302	1.5301
607	1.5525	1.5525	238	1.5297	1.5297
602	1.5519	1.5519	228	1.5294	1.5294
580	1.5500	1.5500	202	1.5285	1.5285
578	1.5499	1.5499	193	1.5582	1.5281
569	1.5491	1.5491	183	1.5278	1.5278
558	1.5482	1.5482	170	1.5274	1.5274
542	1.5469	1.5469	145	1.5265	1.5265
530	1.5458	1.5458	137	1.5263	1.5262
525	1.5455	1.5455	133	1.5261	1.5261
521	1.5452	1.5452	127	1.5258	1.5258
518	1.5450	1.5450	96	1.5241	1.5240
512	1.5445	1.5445	92	1.5237	1.5237
509	1.5443	1.5443	89	1.5235	1.5235
491	1.5430	1.5430	83	1.5229	1.5229
469	1.5414	1.5414	79	1.5224	1.5224
457	1.5406	1.5406	73	1.5216	1.5216
436	1.5393	1.5393	64	1.5200	1.5197
417	1.5381	1.5381	57	1.5183	1.5180
394	1.5368	1.5368	52	1.5155	1.5159
375	1.5358	1.5358	44	1.5123	1.5121
356	1.5348	1.5348	42	1.5103	1.5102
339	1.5340	1.5340	40	1.5086	1.5085
332	1.5336	1.5336	37	1.5063	1.5064
308	1.5325	1.5325	35	1.5030	1.5030
302	1.5323	1.5323	30	1.4952	1.4951
297	1.5321	1.5321	25	1.4809	1.4805
289	1.5317	1.5317	21	1.4625	1.4627
285	1.5315	1.5315	19	1.4415	1.4410
277	1.5312	1.5312	17	1.4152	1.4148
271	1.5310	1.5310	15	1.3736	1.3735
263	1.5307	1.5306	13	1.3407	1.3403

second, and therefore none at all. In the final lecture of this course we shall deal with some relations between light and electricity, the connection between which, according to modern views, is most intimate. Then we shall be in a better position to understand that when there are no vibrations, so that you have a steady electric field, the square of the refractive index must be identified with what has long been known as the specific inductive capacity of the material. This quantity K can be determined by suitable electrical measurements, and when the value so obtained is compared with that derived as indicated above from our formula, there is an excellent agreement between the two measures.

Just one more point and I have done. I have said that the formula gives the refractive indices for frequencies (f), which are not very close to any of the natural frequencies (f_1 and f_2...). If f be close to f_1 or f_2, there will be considerable absorption, and the formula must be modified. Instead of troubling you with symbols, I shall indicate by a figure the nature of the change that occurs in the neighborhood of an absorption band. Let us represent frequencies (f) by distances measured along the horizontal line CDF... in Fig. 10, and the corresponding refractive indices (n) by distances measured at right angles to this line. The dotted curve in the figure indicates how the refractive index varies with the frequency, when we are *not* near one of the natural frequencies. You will observe that the curve rises steadily to the right, indicating that the refractive index increases with the frequency; orange is more refracted than red, and blue more than orange. Next, suppose that we are dealing with a substance that has a natural frequency at D. Then our theory would lead to a formula

connecting n and f, which is graphically represented by the continuous line of the figure. You will notice a striking contrast to the previous case. The refractive index no longer rises steadily as the frequency increases. As the

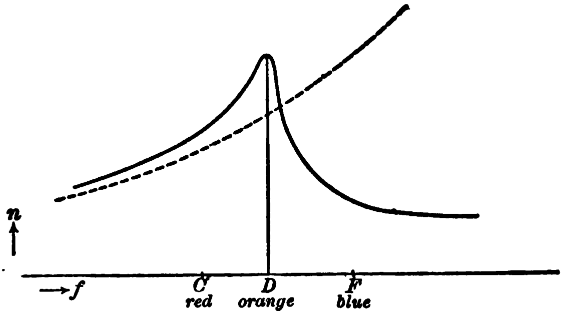


Fig. 10

natural frequency is approached, the refractive index rises abnormally, and it begins to fall and to fall rapidly when the natural frequency is passed. In the special case that I have chosen, orange is more refracted than either red or blue, and blue is even less refracted than red. The order of the colors in the spectrum is thus quite different from the ordinary, and it appeared so lawless when first observed, that the phenomenon was branded with the name *anomalous dispersion.* We now see that there is nothing lawless about it, and that the same theory that enables us to explain ordinary or normal dispersion gives us also the law (of course a different law) for this apparent anomaly.

IV

SPECTROSCOPY

In the last lecture we were occupied a good deal with discussions as to the structure of an atom and a molecule. We saw that, according to the most recent speculations, an atom is no longer regarded as a hard, rigid mass, but as a throbbing, palpitating mechanism, almost a living thing. Such a mechanism is capable of vibrating in various different modes, each with its natural frequency. In any given substance in a given physical condition, the number of the possible modes of vibration and the values of the corresponding frequencies must be perfectly definite. Any periodic movement in the atom or the molecule will tend to set up disturbances in the ether, and these will be periodic and have the same frequencies as those of the vibrations that originate them. Whether such vibrations set up in the ether will produce the sensation of light or not, will depend on their frequency. In round numbers this frequency must lie between four hundred and eight hundred million million per second, as vibrations that are either slower or faster than this do not affect our sight, although their influence may easily be detected in other ways. Let us suppose, for example, that under any given circumstances the molecule is so constructed that it can vibrate in two different ways, with frequencies of five hundred and six hundred million million respectively. These vibrations will set up light of two different colors, and

if the substance be viewed through a circular hole (as in Newton's experiment referred to on p. 15) and the light passed through a prism, we shall see two circular colored patches in different positions, one of them blue and the other orange. If the diameter of each patch be very small, it may be possible to distinguish the two patches easily and clearly; but if the two frequencies be chosen more closely together, the circular patches will almost inevitably overlap, and it will be difficult to distinguish clearly between the two. This overlapping of the different colors would prove a very serious defect if accurate measurements were aimed at, and, had it not been possible to remove the defect, the modern science of spectroscopy would have been impossible. The simplicity of the change required in Newton's arrangement is a striking example of the occasional importance of small things for achievement in science. All that is needed is to replace the circular hole by a narrow slit parallel to the sharp edge of the prism. Then, instead of two circular patches of light on the screen, we have two narrow lines parallel to one another, and unless the two frequencies be nearly coincident, these lines will be clearly distinguished and their positions easily determined with precision and accuracy.

To understand the principles of spectroscopy, you must bear in mind that different lines in the spectrum indicate different frequencies, and each frequency corresponds (as a rule) to a different mode of vibration. Of course much may be going on within the molecule that does not influence our sight (as we have seen, the range of sensitiveness of the éye is limited), and again it may require a stimulus of a special kind, such as a high temperature, to set any particular mode of vibration in action. Thus a substance may be

vibrating in many modes, with frequencies too high or too low for us to see, and we may at one time observe lines in the spectrum of an element which are not visible at all under different circumstances. The important point for

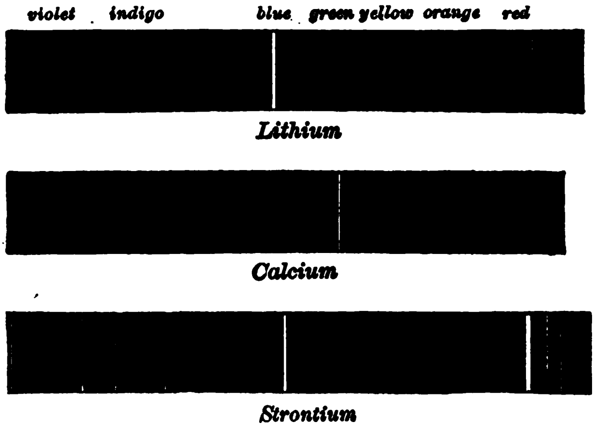


FIG. 11

us at present is that, if we are right in regarding a substance as vibrating with definite natural frequencies, we should expect that its spectrum, viewed under *proper conditions,* would not be a continuous band of color, but a series of *isolated* bright lines, each of a color corresponding to the frequency. And as a matter of fact this is so, as you will see from the experiment to be made immediately, or from Fig. 11, which indicates the position and color of the bright lines in the emission spectra of various elements. It is important to observe that these all represent the spectra of elements that are in the form of *gas or vapor.* If the substance is in the solid or liquid state, its spectrum no longer consists of a series of isolated bright lines, but is *continuous.* This difference in the aspect of the spectrum

of a substance — gaseous in one case, liquid or solid in the other — is of fundamental importance in the theory of spectroscopy, and it may be well to get a glimpse of the reason for the difference. According to the generally accepted view as to the nature of a gas, the molecules of such a substance are in constant motion. Collisions between neighbors are therefore to be expected, the frequency of these collisions depending, amongst other things, on the distance between the neighbors, or on the density of the population. If the gas be not very much compressed, the distance between neighboring molecules will be large enough to allow them to move fairly freely and to execute their natural vibrations without being disturbed by constant collisions. Suppose, however, that the gas is compressed enough to liquefy it, or that further changes are made until a solid is obtained. Clearly the conditions of the molecules have been greatly modified. Instead of being fairly free to move, each is now cabined, cribbed, and confined and, as a consequence, collisions between neighboring molecules are almost constantly taking place. Thus, instead of a few definite modes of vibration, we have vibrations of almost every possible frequency, and the spectrum is continuous. Here in this electric arc you have a solid hot enough to send out a brilliant light. Pass the light through the prism to analyze it, and you see a brilliant spectrum on the screen. You observe that it is perfectly continuous, no sign of a break or an isolated patch of brightness as your eye passes from red to violet, through all the familiar colors of the rainbow. Now place a piece of sodium in the arc. The heat is intense enough to turn it instantly into vapor, and you see at once, in addition to what was seen before, a bright line in the orange. The

solid carbon pencil gives a continuous spectrum, the gaseous sodium an isolated line or series of lines.

You have seen, then, that a substance in the form of a vapor or gas will, if viewed under proper conditions, exhibit a spectrum crossed by certain bright lines. The science of spectrum analysis rests, in the main, on two facts with reference to these lines. In the first place, *the position of the lines is always the same for the same element in the same condition*, and in the second place, *the arrangement of the lines is different for different elements.* Once this is grasped, there can be no difficulty in understanding how the study of spectra enables us to detect the chemical nature and the condition of various substances, whether they be in our laboratories, or in the Sun, over ninety million miles away, or in some star away in the measureless abyss of space.

For purposes of investigation, we need an instrument that will enable us to see these bright lines clearly and measure their relative positions accurately. An instrument specially designed for this purpose is called a *spectroscope.* It is a wonderful instrument, for, although constructed on the simplest principles, it has revolutionized astronomy and done great things for chemistry and physics. We want some means of separating the light that arises from the different natural vibrations with different frequencies; in other words, we want *dispersion.* The simplest instrument for producing this is that employed to such good purpose by Newton, the prism. Figure 12 shows four such prisms (*P*) mounted between two telescopes, *A* and *B*, so as to make a spectroscope of the simplest type. The light from the substance to be examined passes through a narrow slit into telescope *A*, and after being bent and dispersed by the prisms, it enters telescope *B*, and impresses itself on

an eye looking through this telescope. The instrument may have only a single prism, but this will not produce great dispersion, and may not separate the various lines as widely as is desired. To increase the dispersion, two or more prisms are employed, the light passing through one after another and being more dispersed at each passage. This

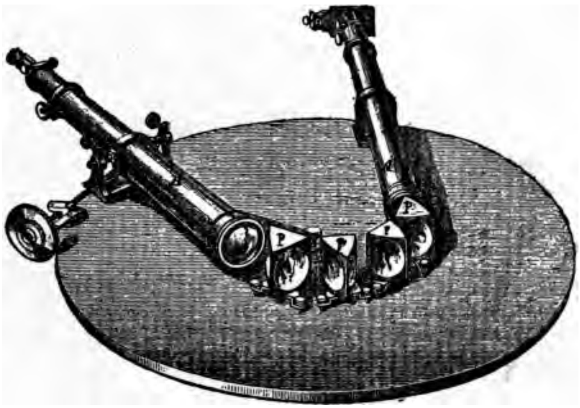


FIG. 12

arrangement has the defect that a considerable amount of light is lost by reflection and absorption, and the loss may be so great that the fine lines are not clearly visible. To avoid this serious defect, the more modern spectroscopes employ another means of producing large dispersion. The prism is replaced by a *grating*, a contrivance for dispersing light, the principle of which will be dealt with in a later lecture on diffraction. Two distinct forms of grating have been invented. The first was made by ruling a series of fine lines on glass or speculum, and was perfected by Rowland of Baltimore; the second, the echelon spectroscope, due to Michelson of Chicago, consists of a series of thin glass

plates piled on one another like a flight of steps. To a spectroscope of any of these forms a photographic apparatus may be attached so as to obtain a permanent record on a plate instead of a passing impression on the eye. Such an arrangement is called a *spectrograph,* and it is one of the most important instruments in an astrophysical observatory.

On looking through a spectroscope at a luminous object, you see its spectrum. If the spectrum be continuous, you know that you are looking at a *solid* or a *liquid* hot enough to emit light; whereas, if the spectrum be discontinuous, you are looking at a gas. Thus a mere glance through a spectroscope enables you to tell in a moment something of the physical condition of an object, and this whether the object be near or far. In this way we know that comets are mainly glowing gas, and so are many nebulæ. In all the wonders of the heavens, few things are so impressive as the gigantic cloudlike forms, such as the great nebula in Orion. Is each of these a vast collection of stars like the Milky Way, or is its structure quite different from this? After much difference of opinion among astronomers, the question was finally settled by Sir William Huggins, one of the pioneers of spectroscopy. "On the evening of August 29, 1864," he says, "I directed the spectroscope for the first time to a planetary nebula in Draco. I looked into the spectroscope. No spectrum such as I had expected! A single bright line only! . . . A little closer looking showed two other bright lines on the side towards the blue, all three lines being separated by intervals relatively dark. The riddle of the nebulæ was solved. The answer which had come to us in the light itself read: *Not an aggregation of stars, but a luminous gas.*"

Thus the spectroscope tells us something of the physical condition of a substance. It shows whether it is gaseous or not. But it does much more than this; it reveals the chemical constitution. This is settled by noting carefully the *positions* of the various lines in the spectra, and comparing them with the positions of lines in the spectra of known elements. A glance at Fig. 11 will serve to recall the fact that the spectra of no two different elements are the same, so that if we see in the spectrum of any substance the characteristic lines of any element, *e.g.* hydrogen, we can be certain that the substance contains hydrogen. A more careful examination of the various spectra makes it evident that the chance of confusing two elements is extremely small. We now possess very carefully made maps of the spectra of the elements, and these greatly facilitate the process of identification. This spectroscopic method of examining the chemical constitution of a substance is a very simple and a very valuable one. Its extreme delicacy enables us to detect the presence of minute quantities of a substance that no ordinary chemical process could possibly detect. Morever, the fact that a different series of lines in the spectrum indicates a different element shows that if we find spectra differing from any already known, we have good ground for supposing that we are in the presence of a new element. And so it happened that one of the first fruits of the science of spectroscopy was the discovery of new elements. Bunsen was the pioneer in this field. In 1860 he discovered in this way the elements *Cæsium* and *Rubidium;* in the following year Crookes discovered *Thallium,* and there has been a long list of similar discoveries since then.

This spectroscopic method of distinguishing one substance

from another by the *positions* of the lines in their spectra has, during the last half century, become one of the commonplaces of chemistry. In recent years, however, the attention of physicists has been directed to other features of the lines than their mere positions. Even a slight examination reveals the fact that there are various differences between the lines, *e.g.* one is much broader, or much brighter, than another. In these latter days each line is subjected to the most minute examination, the pioneer in this field of investigation having been Michelson of Chicago. By means of an ingenious instrument of his own invention, — the interferometer, an instrument the explanation of which depends on the principle of interference that is dealt with in a later lecture, — he observes certain features of the lines, and records the results of his observations graphically in the form of what he calls *visibility curves.* If you look at those curves for different substances, you will see that one line differs very markedly from another. Here, for example, in Fig. 13, are the curves for different lines in the spectra of various substances: (*a*) for the red line of cadmium, (*b*) the red line of hydrogen, and (*c*) the green line of mercury. From the study of the form of these lines, Michelson makes various interesting and important deductions as to the character of the source that sends out the light radiation. He concludes that (*a*) comes from a source of the simplest possible character, a single vibrator sending out waves that are almost perfectly homogeneous. The form of (*b*) seems to indicate that the source is more complex than with (*a*), and Michelson concluded that the radiation came from two sources, differing very slightly in frequency and in intensity. His prediction as to the essentially double character of this line was afterwards confirmed by direct obser-

vation. The curve (*c*) reveals a much more complex source; in this case, apparently, the radiation comes from a number of vibrators differing both in frequency and in intensity. The interest of such investigations centers entirely on the light that it sheds on the fundamental problem of the struc-

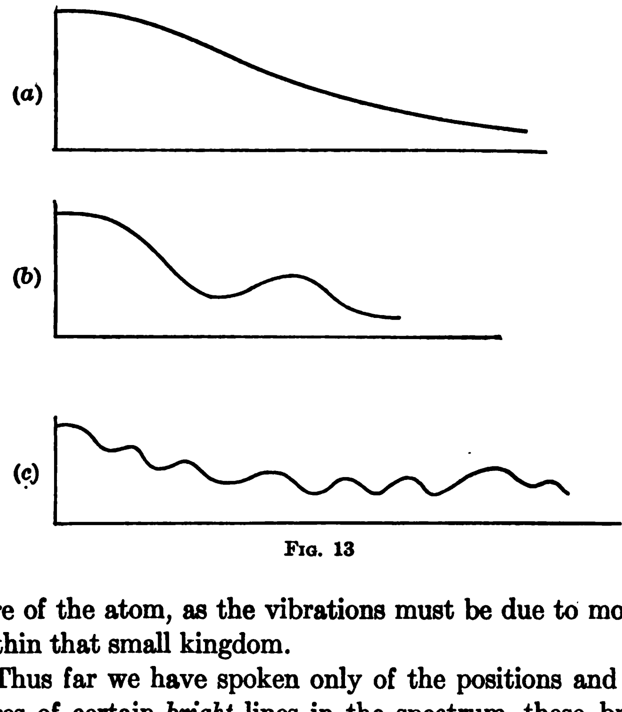


FIG. 13

ture of the atom, as the vibrations must be due to motion within that small kingdom.

Thus far we have spoken only of the positions and features of certain *bright* lines in the spectrum, these bright lines being separated by spaces that are relatively dark. On looking at the solar spectrum with a good spectroscope, a different phenomenon is revealed. The spectrum is seen to be bright and all but continuous except that it is crossed by a large number of fine *dark* lines. These lines were

first carefully observed by Fraunhofer in 1814, and are still known by his name. In the intervening century they have been studied with the greatest care, and the task of mapping them accurately has been undertaken and carried out with marvellous patience and skill. Thus Rowland's map records the places of about tweny thousand of these lines. What is their meaning, and why should we trouble to record their positions with so much care? After the last lecture on absorption, we should have no difficulty in answering such questions. A vibrating system absorbs the energy of waves that have the same frequencies as the natural frequencies of the system. Look at the spectrum of the vapor of sodium. You will see two bright lines (*D*) close to one another in the orange, and the positions of these lines depend upon the frequencies of the natural vibrations of the sodium atom. If now a train of waves passes through the sodium vapor, those waves will have their energy extracted that have frequencies corresponding exactly to those of these two *D* lines. Hence, if the light that falls upon the sodium vapor come, let us say, from a glowing liquid hotter than this sodium, the continuous spectrum of the liquid will be crossed by two *dark lines* coinciding in position with those *D* lines. This is the phenomenon of *reversal*. It is no mere deduction from theory, but a fact, verified, as you see, by the experiment that is being conducted before you. The principle involved in the explanation here given had occurred to Stokes and other physicists in the first half of last century; but it was reserved for Kirchhoff in 1859 to set it forth clearly and test it by experiment. From that date we may mark the rise of what is often called the new astronomy — an application of spectroscopic methods to the study of the physi-

cal condition of the heavenly bodies which has led to many epoch-making results.

In Fig. 14 the phenomenon of reversal is exhibited by showing side by side the bright lines of the emission spectra, and the dark lines in the absorption spectra of a few elements. The point to be specially noticed is the coinci-

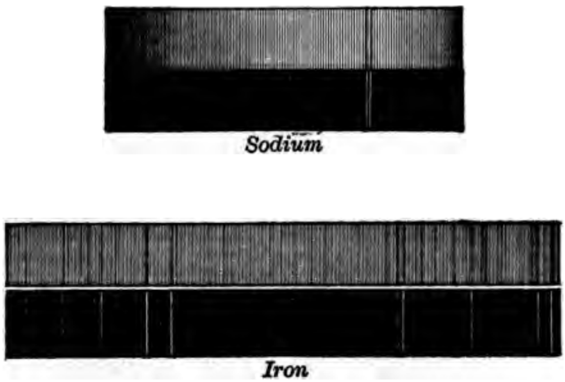


FIG. 14

dence in position of the bright lines in one case with the dark lines in the other. It may at first be thought that these coincidences are only accidental. This might, indeed, be so were there only a few coincidences, but the number actually observed puts the idea of chance out of the question. Thus, in the case of the iron lines, Kirchhoff, on taking into account the number of the lines, their distances from one another, and the degree of exactness with which their positions could be determined, calculated that the odds were at least a million million million to one against a mere chance coincidence. We may thus feel practically certain that, when we see dark lines in a spectrum coinciding in

position with bright lines in the emission spectrum of an element, we are looking at the light from a hot source shining through a cooler vapor containing the element in question. It will be realized at once that this enables us to detect the presence of elements in any body, be it near or far, that is in a certain physical condition. What this condition is should be carefully borne in mind. The body must be hot enough to give a continuous spectrum, and it must be surrounded by a *cooler atmosphere.* The spectroscope then enables us to determine the ingredients of this atmosphere. Naturally, the method was first tried upon the Sun, and the observation of the Fraunhofer lines and the comparison of their positions with those of the bright lines in the spectra of various elements have made a great advance in our knowledge of solar chemistry possible and easy. In this way a very large number of familiar elements have been discovered in the Sun, so many that it may be simpler to mention a few that have *not* been found there, such as gold, arsenic, mercury, nitrogen, and sulphur. There are still a great many unidentified lines in the solar spectrum, some twelve thousand having been registered that are as yet without chemical interpretation. Clearly, the method here sketched is not confined to the Sun but is applicable to any body whose spectrum can be examined. Thus, for example, we now know with certainty that many of the stars are made up of much the same material as our earth, and that they are in much the same condition as the Sun, that is, they are hot bodies surrounded by a gaseous atmosphere.

Turning, for a moment, from stellar chemistry to more mundane matters, we may observe that the careful study of absorption spectra may yet help us to solve many funda-

mental problems in molecular physics and chemistry. In this field much useful work has already been done by Hartley and others in the examination of the absorption spectra of various organic compounds. These compounds are formed by grouping different elements round a carbon atom, and a fundamental question is: How are the atoms arranged? if you could see them, what would be their relations to one another in space? Such questions can sometimes be answered, with more or less assurance, by the careful study of the nature of the chemical reactions of the substance under different circumstances. But often this method fails, and Hartley shows that the study of absorption spectra may help us out of the difficulties, and enable us to say, for example, that in a certain compound the hydrogen atom is linked to the nitrogen and not to the oxygen. A mere change of linkage, that is, a change of grouping, can modify the spectrum, and the study of such changes bids fair to give us an insight into the actual arrangement of atoms in the group.

FIG. 15

In dealing with so extensive a subject as spectroscopy in a lecture such as this, it must soon be realized that there is not sufficient time to do more than speak of its fundamental principles and point out a few of its most striking achievements. Some of the latter have already been indicated; let us glance at a few more. Spectroscopy enables us to discover not only the physical condition and chemical nature of various heavenly bodies, but also, in certain circumstances, the speed at which they are moving. To understand this, suppose that you are sitting in a canoe at A (Fig. 15), and that you set up a series of waves by dipping your paddle

into the water once a second. If V be the speed with which the waves move over the surface of the water, the first wave will reach B at a time $\frac{AB}{V}$, and the second at a time $1 + \frac{AB}{V}$, both times being measured in seconds from the moment when your paddle first touched the water at A. The *interval* of time between the two waves reaching B is one second. This will be the case whatever be the velocity V, so that a change of velocity does not affect the time interval between the waves that strike upon B; in other words, it does not affect the *frequency* of the oscillations at B. But now suppose that you paddle your canoe toward B with velocity v. The first wave reaches B at the time $\frac{AB}{V}$ as before. The second wave again starts one second later, *but it has not so far to go* in reaching B. It goes only the distance $CB = AB - v$, so that it arrives at B at the time $1 + \frac{(AB-v)}{V} \quad \frac{AB}{V} + 1 - \frac{v}{V}$. The interval of *time* between the first and second waves that reach B is thus changed from 1 to $1 - \frac{v}{V}$ (and it would be easy to show in a similar way that the interval would be changed to $1 + \frac{v}{V}$ if you paddled in a direction *away from B* instead of *towards* it). This change of interval means, of course, a change of frequency in the oscillations observed at B. You will see that there is nothing in the argument that limits its application to water waves; if true at all, it should apply equally to waves in water, or any other medium, such as air or ether. The only difficulty in its application to light is that a careful scrutiny reveals some rather delicate questions as to the

relative motion of ether and matter, questions that it would be out of place to discuss on this occasion. The principle itself was first clearly stated by Doppler in 1843, and was tested two years later by observations on sound from locomotives. The theory of sound shows that the pitch of a note depends on the frequency of the oscillations in the air that strikes upon the ear. Hence, according to Doppler's principle, the pitch of a note should change in a definite way, as the source of sound approaches and recedes from an observer. The general character of the change can be observed by any one who cares to listen carefully to the sound of the bell when a bicycle passes him in the street. The object of the experiments referred to was to test the principle in a more thorough fashion by exact measurements of the pitch, and the results showed clearly that the principle was well grounded in fact.

To understand the application of Doppler's principle to spectroscopy, you have only to recall the fact that the positions of the lines in the spectrum depend upon the frequency of the vibrations. Consequently, a change of frequency should reveal itself by a shift in the positions of the spectral lines, and a measurement of this shift gives us the means of calculating the velocity of the source of light (say a star), or rather the component of its velocity in the direction of the line of sight. Many interesting results have been obtained by this mode of research. Thus, for example, it has enabled us to estimate the speed of different parts of the Sun, such as the mighty currents of gas in the neighborhood of a Sun spot, or those awe-inspiring tongues of flame (the prominences) that shoot up from the central fire of the Sun, in some cases at the rate of about seven hundred miles per second. Similarly, it has made it pos-

sible to determine the speed of many stars that are far too distant to have their velocities gauged by any other method. As is to be expected, the velocities are found to be very different for different stars. Some are moving relatively to the Sun at about one mile per second, others at nearly a hundred miles. The majority on one side of the heavens have a general relative motion *towards* the Sun, those on the opposite side a similar motion *away* from the Sun. The inference, of course, is that the Sun itself is not stationary, but is sweeping through space with his attendant train of planets. Another interesting achievement of this mode of research is that it has enabled us in many cases, in a sense, to see that which is invisible. In general, no star can be seen unless it be hot enough to emit light, and yet, though unseen, its presence may be none the less distinctly felt. Whether hot or cold, it will still have weight, and will have the mystic power of gravitation, of attracting all neighboring bodies towards itself. If heavy enough, it will compel its neighbors to move round it in definite orbits, like the planets round the Sun. If we see a star moving round an orbit, we may be certain that it has a companion that attracts it, whether this companion be visible or not, and the principles of celestial mechanics may enable us to determine various facts about this dark companion — for example, its weight. Now the observation of the shifting of the lines in the spectrum of various stars, when conducted over a long period, often shows that the stars are not moving uniformly in a definite direction, but are circling round an orbit, and so from the knowledge of the visible we are led to infer the presence of the invisible. The application of Doppler's principle also occasionally gives us information as to the structure of the heavenly bodies. Among the

most striking objects to be seen with a good telescope are the beautiful rings of Saturn. What is the structure of these rings? This was a question long debated, until Maxwell in 1859 showed by means of mechanical principles that the rings could not possibly be solid, for in such a state they would be unstable and would fly to pieces. The argument convinced all those who were not afraid of the highroad of mathematics and mechanical science, but it was not till 1895 that we had ocular demonstration that Maxwell was right. In that year Keeler showed, by a careful study of the spectra of the light reflected from the rings, that the *inner* edge is moving faster than the *outer*, which of course would be impossible with a solid. As Maxwell had indicated, the ring is a group of meteorites, each moving as a separate planet round Saturn as its central Sun.

So much for Doppler's principle and its applications; let us turn to some other phases of the modern science of spectroscopy. We have had occasion to refer to the solar prominences, those mighty tongues of flame that shoot outwards from the Sun to distances, sometimes, of several hundred thousand miles. Huge and brilliant as they are, they are not to be seen under ordinary circumstances with the naked eye, for their brightness is overpowered in the glare of the sunlight. And so, until forty years ago, they were thought of only as an eclipse phenomenon, and were looked for eagerly on those rare occasions when at any given place the Sun is seen in *total* eclipse. All this was suddenly changed by an epoch-making application of the spectroscope — an application due to the ingenuity of Janssen, Lockyer, and Huggins by means of which the prominences may be seen on any day. The principle of the arrangement is very simple. A spectroscope *disperses* the sunlight that

passes through it; it spreads out the image of the narrow slit from, say, one-thousandth of an inch to many feet. This dispersion, as we saw in an earlier lecture, is due entirely to the different refrangibility of the various constituents that go to make up the composite thing that we call sunlight. *Homogeneous* light, light of a definite refrangibility, is *not dispersed.* Now it so happens that the solar prominences are made up mainly of homogeneous light, such as the light from hydrogen or helium or calcium. Consequently, while the light from the Sun is spread out by the spectroscope, that from the prominence is not. Hence, by employing a spectroscope of sufficient dispersive power, it is possible to spread out the sunlight so much that the prominence looks bright in comparison with the Sun, and may be plainly seen on any day of the year, without the tedium of waiting for a total eclipse.

That was an ingenious and important device; but even more so was the later development due to Hale (now of the Mt. Wilson Solar Observatory). This device enables us not only to *see* the prominences at any time, but to *photograph* them, and thus obtain a permanent record of their features. The form of spectroscope specially designed for this purpose is known as a *spectroheliograph.* Let us see how it works. A special feature of the solar prominences is the presence therein of quantities of the vapor of calcium, the spectrum of which is characterized by two bright lines called *H* and *K*. Suppose that we present the slit of the spectroheliograph to a prominence, so as to allow the light from the prominence to stream through the instrument. In this way we look, as through a narrow window, at a section *ABCD* (Fig. 16). The light from this section, if passed through a prism or other dispersing apparatus, would be drawn out into a

spectrum, and if you were to put your eye in the position of the line K, you would be in a position specially favorable to receive impressions from light that came from the vapor of calcium. As this vapor is an important ingredient in the prominence, the portion BC of the section that you were observing, would appear much brighter than the portions AB and CD that lay outside the prominence. In this way the cross-section BC of the prominence would stand out more or less distinctly, and by moving the slit up and down, you could thus observe various cross-sections, and so map out the whole prominence. To obtain a permanent record, it is necessary to replace the eye by a photographic plate, in front of which a second slit is placed in such a position that it catches the light from calcium vapor, but no other kind of light. A suitable mechanism moves the slits so as to give a succession of photographs corresponding to different cross-sections of the prominence.

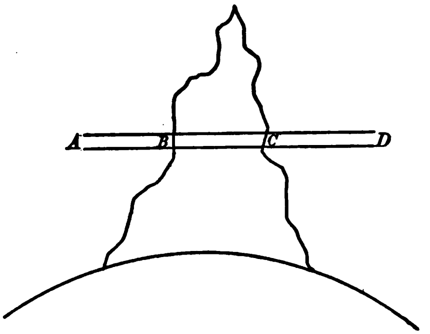


FIG. 16

The method here sketched was first tried with complete success by Hale in 1892. He saw at once that it could be applied to the study of other solar features. If, for example, there were a cloud of calcium vapor anywhere in the Sun's surface, the same method would enable the observer to pick it out and photograph it. Hale did this in 1892, and his more recent photographs of *calcium flocculi* reveal the

fact that these beautiful clouds are specially striking in the neighborhood of Sun spots. Then, of course, there is no reason to confine the method to photographing clouds of calcium. Other elements may be dealt with similarly. In this way, working with one of the hydrogen lines, Hale found that great masses of this gas are concentrated in clouds on various parts of the Sun's surface, and photographs of these *hydrogen flocculi* show them to be so numerous as to make the bright face of the Sun present a distinctly mottled appearance.

We have seen that the spectroscope enables us to detect the presence of familiar chemical elements in the Sun and stars, to measure the velocities of such distant bodies, and to photograph many otherwise invisible features on the face of the Sun. We have also seen that it may give us an insight into the physical condition of various heavenly bodies. A continuous spectrum indicates a glowing solid or liquid, while a discontinuous spectrum reveals a gas. But we can often tell more than that the object of our interest is a great mass of gas. We may learn something of its temperature and of its pressure. It is found by observation that the relative intensity of different lines varies with the temperature of the source of light. For example, in the spectrum of magnesium, there are two lines, *a* and *b*, say; of these two, *a* is brighter than *b* at the temperature of the electric spark, but *b* is brighter than *a* at lower temperatures. This may serve to indicate how the relative intensity of the lines in the spectrum may serve as a clue to the temperature of the glowing gas. Moreover, the character of the spectral lines is altered by a change of pressure. If the pressure be increased, the lines broaden, so that an observation of their width tells us something of the pressure of the gas.

It is even possible to take a photograph (by means of a spectroheliograph) of the calcium vapor at the *base* of the calcium flocculi in the Sun, without being troubled by the lighter vapor above. To do this, it is merely necessary to set the second slit of the instrument near the edge of the *broad K* bands, so that the light from the rarer vapor cannot enter the spectroscope, and is thus debarred from affecting the photographic plate. Such a device has made it possible to learn a good deal of the structure of these flocculi, by examining sections of them taken at various levels.

The last point that there is time to touch upon is the contribution that spectroscopy has made to our knowledge of the trend of stellar evolution. This idea of development, or evolution, if you prefer the term, has become a commonplace of modern thought in almost every field of speculation and of knowledge. It is an old idea, brought, as you all know, into a precise form that immediately appealed to man's imagination by Darwin in his *Origin of Species* — that epoch-making book that was published in the same year in which Kirchhoff laid the foundations of the science of spectroscopy. Long before Darwin's day, the idea of stellar evolution had been broached, the idea that the heavenly bodies have not been always as they are to-day, but that they have been and still are going through a gradual process of change. To unravel this secret of the universe and get some insight into the earlier history and later destiny of the worlds around us is one of the grandest problems that the pygmy man has been bold enough to attack. Kant, the great philosopher, made some suggestive speculations, and Laplace, the great mathematician, developed them into a definite working hypothesis. But

all such thinking was somewhat premature. If you wish to trace the development of anything, you must know as accurately as possible its physical condition at various stages of its growth. People are naturally somewhat skeptical when they are asked to believe that their remote ancestors were probably arboreal in their habits; but they are really not in a position to judge of the merits of such a theory unless they have made a careful study of the different stages of human development. And so with the problem of stellar evolution it is necessary to begin by finding out all that can be known of the actual physical condition of different members of the heavenly host. Spectroscopy is making the solution of the problem possible; it cannot be said to have solved it yet. By means of this science we now know a good deal as to the physical conditions of a very large number of heavenly bodies. We can thus arrange these bodies into groups, the members of each group having certain properties in common, and it *may be* that these groups represent different stages in a general process of development. Suppose we put them into six groups, and look at each very briefly. *First,* there are the nebulæ. Many of these are enormous clouds of glowing gas, the bright lines in their spectra indicating the presence of hydrogen and helium, and of an unknown element which has been given the name *nebulum.* Out of these cloud-like masses we might expect various forms to be evolved, through the action of gravity and other forces, and in view of certain speculations as to the mode of their evolution it is interesting to observe that of 120,000 nebulæ that have been examined, more than half have a spiral form. They look like mighty Catherine wheels in the very act of whirling. *Second,* we have the special class of nebulæ that con-

stitute the Orion type. Their spectra exhibit no bright lines except those of hydrogen and helium, and these lines are very broad and faint. *Third* are the white stars, such as Sirius. Their spectra show broader lines of hydrogen, with narrow and faint dark lines of iron, sodium, magnesium, and a few other elements. Their atmospheres are still very rare, much rarer than that of the Sun. *Fourth* come the yellowish stars like the Sun. They have far more dark lines in their spectra than their predecessors, and there is evidence of much greater density. *Fifth*, we have the red stars, of which Antares is a type. They are beginning to fade into invisibility. Their spectra are much more complex than those of the previous groups, and contain a great many lines, and not a few dark bands or flutings. *Last* come the dark, invisible stars. They are too cold to give any light, and can be detected only, as already indicated, by the shifting of the lines in the spectrum of a neighboring bright star.

Here, at any rate, we have food for thought. We may feel certain that some process of development is in progress, for nothing that we know well stands quite still. But what is the exact order of the development, whether that order is everywhere the same, and whither it all tends are questions we may hesitate to answer. Here, probably the better part of valor is discretion. Later researches have revealed many difficulties in Darwin's theories, and put many a stumbling-block in the path of him who is too eager to embrace the nebular hypothesis of Kant and Laplace as to the mode of stellar evolution. The leaders of thought in this field must work with patience and endurance perhaps for many a generation before there is anything like a final concord in answering these great questions. I leave them with you as food for speculation

and, if vastness attracts you, here you have some problems preëminently to your taste. You are not asked to decipher the history of man, nor to tell the tale of the "solid" earth, which is the scene of all his thinking and activity, but to describe the birth, the struggles, and the end of the universe.

V

POLARIZATION

LET me direct your attention to an experiment that you may all repeat without difficulty. I take a sheet of ordinary glass, ACB (Fig. 17), and hold it between my eye, E, and the light, L, so that EL is perpendicular to the plane of the glass. As I turn the glass round, keeping C unmoved, and the plane of the glass always at right angles to EL, the light maintains a uniform brightness. Now I put in a second sheet of glass, $A'C'B'$, and hold it parallel to the first. The light does not look quite as bright as before, but it is still true that its intensity is unchanged by any turning of the first piece of glass in the manner that has been described. Next let us modify this experiment by substituting for the glass a substance almost as transparent. Here is some Iceland spar made into the form of a Nicol's prism. On putting it before the light of the lantern, you see how transparent it is by observing how brilliantly the screen is illuminated by the light that streams through the prism. Another prism similar to the first is now introduced, and you observe that as this prism is turned round, exactly as was the glass with which we began, the brightness of the screen is no longer constant,

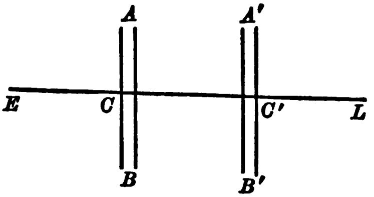


FIG. 17

but is varying continuously. Now the screen is exceedingly bright, and now that I have turned the prism a greater way round through ninety degrees, *there is no light at all on the screen.* Further turning gradually restores the light until a full half turn has been made, when the screen is as brightly lit up as ever, and so the cycle goes on until again all the light is extinguished. This is certainly a curious phenomenon, the cutting off of light by means of a transparent substance merely by holding it in the right position. The explanation of the phenomenon involves the discussion of the *polarization of light,* a subject interesting in itself and of the first importance in the development of optical theory.

You have already been reminded that light is to be regarded as due to a to-and-fro oscillation, a wave-motion propagated in a medium that is called the ether. Let us suppose that such a disturbance enters this room by the north wall and that, at any instant of time, every element of ether on that wall is moving similarly. We should speak of this wall as the wave-front, and in due time, as the disturbance was passed on from element to element, this wave-front would move across the room and reach the south wall. So far we have said nothing as to the *direction* of motion of each element in the wave-front; we have merely said that the motion is of a vibratory character, each point moving to and fro and returning to its original position with a definite frequency. It now becomes necessary to specify more definitely the character of this motion, and the first point to bear in mind is that, for reasons that will be indicated almost immediately, we must think of all the elements in a wave-front as moving entirely *in that plane.* In the case just referred to, if we could see the ethereal

elements as the light entered the north wall of the room, each of these elements would be moving in a little orbit, *every point of which would be on the north wall.* Of course this restricts the possible movements of the ether very much; it confines them all to the wave-front, but there

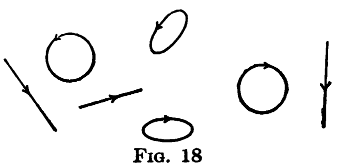


FIG. 18

is still a great deal of freedom. Orbits of all sorts might be described, some elements might be vibrating to and fro along a line, some in circles, others in ellipses, and others in more complex orbits — always with the restriction that the plane of these orbits must be the wave-front. Such a system of multiform orbits is depicted in Fig. 18, the plane of the paper representing the wave-front, and if such a condition of things existed, the light would *not* be polarized. The

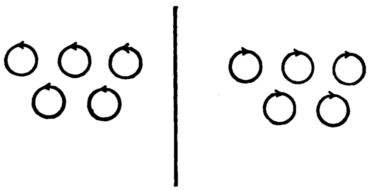


FIG. 19

peculiarity of polarized light is that all these orbits are similar. If they are all circles, as in Fig. 19, the light is said to be circularly polarized. The circular orbits may be described in two different senses, clockwise and counter-clockwise, and these are usually distinguished as right-handed and left-handed polarization. Again, the orbits may be all similar and similarly situated ellipses, as in Fig. 20, and this constitutes elliptical polarization. Or all the elements of the ether may vi-

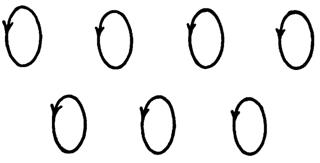


FIG. 20

brate backward and forward along a series of parallel lines. This is rectilinear polarization, or what is more generally called plane polarization. The plane at right angles to the wave-front and through the direction of displacement is called the *plane of polarization*. Fig. 21 represents two cases of plane polarized light, the planes of polarization being at right angles to one another.

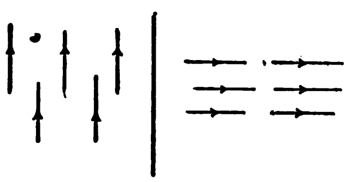


FIG. 21

The case last dealt with, that of plane polarization, is one of special simplicity and special importance. The vibrating elements are all moving backward and forward along a series of parallel lines. This type of motion is well illustrated by looking at a string, AB (Fig. 22 *a*), which is held taut, with its ends fixed at A and B. If the string be plucked aside very slightly at C, its elements will vibrate to and fro in the plane ACB, the various points moving along lines at right angles to AB. In this case ACB is the plane of polarization, and it should be noted that, as the wave of disturbance progresses along the string, the motion of each point is in the wave-front at right angles to the string, the vibrations being of the type described as *transverse* vibrations. If the vibrations be *longitudinal* instead of transverse, we have another important type, whose leading features can be illustrated by the motion of an *elastic* string, AB, which is kept taut as before. If now a point C be moved to C' (Fig. 22 *b*) along the string, instead of at right angles to it,

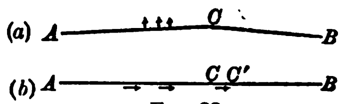


FIG. 22

a longitudinal wave will move along the string, and the various elements will vibrate to and fro in the direction *AB*. These two types of vibrations differ in one very important particular, *the transverse can be polarized, the longitudinal cannot.* The peculiarity of a polarized vibration is that each of the moving elements is constrained to move in a similar orbit, and it is evident that this can be done with the string vibrating tranversely. With the longitudinal vibrations, on the other hand, only one direction of motion is possible, and if this be stopped, there can be no vibration at all. Hence it follows that if light can be polarized, the vibrations must be of the transverse and not of the longitudinal type; the displacements in the ether must be *in the wave-front,* and not at right angles thereto. We shall see presently that the experiment made at the outset of this lecture with the Nicol prisms is easily explained if we recognize the possibility of polarization, but otherwise it is inexplicable. It is for this reason that this experiment is crucial in the theory of light. The idea of accounting for optical phenomena by ascribing them to motion in the ether is an old one, but in the earlier days this ether was always thought of as an extremely rare medium, a sort of idealized gas rarer than anything of the kind that we know of by experience. Now a gas can not propagate vibrations except those of the longitudinal type, such as the waves in the air that produce the sensation of sound. To transmit transverse vibrations, a medium must be able to resist certain changes of shape; it must have some *rigidity,* like a piece of steel. This proved a great stumbling-block to many, even to such leading men of science as Arago and Fresnel, when the phenomena of polarization seemed to force upon them the idea of

transverse vibrations in the ether. Fresnel admitted that he "had not courage to publish such a conception"; but Young and other men were bolder, so that the idea of transverse ethereal vibrations is now a commonplace, and the notion of an ether with some rigidity has lost its terrors.

We have already made use of a vibrating string to illustrate the meaning of a plane polarized wave, and we may

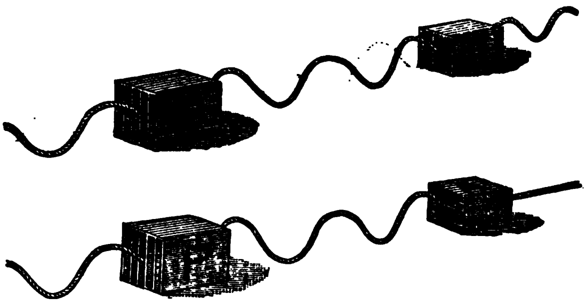


FIG. 23

use it also to throw some light on the experiment with the Nicol prisms at the outset of this lecture. I have here a rope, and as I move one end of it, you observe a wave of disturbance passing along the rope, and the rope being quite free, the displacements may be in any directions at right angles to the rope. Next I pass the rope through this simple wooden structure *P* of Fig. 23. You will observe that it is a box divided up into narrow compartments by a series of parallel partitions that are just wide enough apart to allow the rope to pass freely between two consecutive partitions. The effect of passing the rope through this apparatus is to *polarize* the wave of displacement that passes along the rope. If the partitions are vertical, the displacements are all con-

fined to a vertical plane, so that we have a plane polarized wave, the plane of polarization being vertical. Now if I take a second box, A, similar to the first, P, and hold it with its partitions vertical (*i.e.* parallel to those of the first box), you will observe that when the rope is passed through A as well as P, the disturbance that gets through P is freely transmitted through A also. Suppose, however, I turn A somewhat, so that its partitions are no longer parallel to those of P, then you will observe that A destroys some of the motion in the rope after it has been transmitted through P, and that when A is turned so that its partitions are horizontal, and therefore at right angles to those of P, then, however violently I move the end of the rope, there is absolutely no disturbance that gets through both boxes. Now we shall see in a later lecture, when dealing with crystals, that a crystal acts upon a beam of light somewhat in the same way that this apparatus acts upon our rope. It will not permit vibrations to pass through it, unless they are confined to one or other of two planes at right angles. The effect is the same as if we had a number of obstacles symmetrically arranged, as are the shaded portions of Fig. 24. Any one setting out from O could not proceed along a straight line (such as Oa) for any distance without being stopped by an obstacle, *unless they moved along one or other of the two lines Ox and Oy, which are at right angles to one another.* A to-and-fro motion along these directions might be maintained

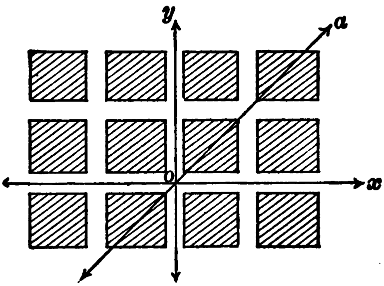


FIG. 24

indefinitely, but in no other direction would it be possible. The Nicol's prism used in our experiment is a simple and ingenious instrument made of the crystal Iceland spar, and so arranged that of the two waves that might be propagated (each plane polarized at right angles to the other) one is got rid of by total reflection. Thus a Nicol's prism acts upon light in such a way that the only light that can get through the prism is plane polarized in what is known as the principal plane of the prism. If, then, we hold two Nicols with their principal planes parallel, this corresponds exactly to the case of the two boxes with their partitions parallel, and the light that comes through the first is freely transmitted by the second. On turning the second Nicol, a change is made, and if it be turned so that the two Nicols are crossed, that is, if their principal planes be at right angles, we have a state of affairs similar to that with the boxes, the partitions of one being vertical and of the other horizontal. Under such circumstances we have seen that no disturbance in the rope can be propagated through both boxes, and no light gets through both Nicols.

I hope that enough has been said to make clear the meaning of polarization, and particularly of plane polarized light. Now when a beam of plane polarized light passes through a solid like glass or a liquid like water, its plane of polarization on emergence is the same as it was at entrance. This, however, is not the case with all substances, a large number being so constituted that the emergent light is polarized in a different plane from the incident. Under such circumstances the plane of polarization has been *rotated* through a certain angle, and this phenomenon is consequently spoken of as the rotation of the plane of polarization of light, or more briefly as *rotatory polarization*. If you care

to see the phenomenon, it is very easily exhibited with the apparatus before you. You will observe that after a little adjustment these two Nicols are now "crossed," with their principal planes at right angles, so that no light can get through them both. Now I place between the Nicols this plate of quartz, and you see at once that the screen is illuminated. However, on turning one of the Nicols gradually, you see that we reach a position where darkness once more reigns, and a very little consideration will show you that this is what we should expect if the quartz has the power of rotating the plane of polarization of the light that passes through it, and that the amount of this rotation is measured exactly by the angle through which it was necessary to turn the Nicol to produce darkness again after the quartz had been introduced. This phenomenon of rotatory polarization is a very interesting one; we shall be occupied with it exclusively during the remainder of this lecture. It will be advisable, however, to postpone the consideration of the very important case when the rotation is effected by the influence of magnetism, as that case will be taken up more appropriately when we are dealing with the relations between light, electricity, and magnetism in the concluding lecture of this course.

Substances that are endowed with the power of rotating the plane of polarization of light may differ as to the direction as well as the magnitude of the rotation that they produce in any given circumstances. Some may rotate the plane as if you were turning an ordinary screw to the right, while others rotate it to the left. Such substances are distinguished by various names, such as right-handed and left-handed, or dextro-rotatory and lævo-rotatory, and wherever they have the rotatory power at all, they are spoken

of as *optically active*. There are two main classes to be considered: in the first class are certain crystals, and in the second certain organic substances in solution. In both cases experiment proves that the angle of rotation is proportional to the thickness of the active medium traversed by the light, so that the rotation produced by a given thickness may be taken as a measure of the rotatory power of the substance.

The most obvious thing about a crystal is that it differs from a non-crystal in having a definite structure. It is not a formless thing like a piece of glass. If you could watch the process of crystallization, you would see a definite form being built up as if by the unerring hand of a skilful artist. You might expect, then, that this fundamental difference between crystalline and non-crystalline media would have something to do with the explanation of rotatory power. And there can be no doubt that it has, the only doubt being as to the actual arrangement of the molecules in any crystal, and the mode in which this arrangement makes the crystal optically active. That there is an intimate relation between structure and rotatory power was shown long ago by Sir John Herschel. It was known that some specimens of quartz rotate the plane of polarization to the right, while others rotate it to the left. Herschel found that this difference went hand in hand with certain differences of crystalline form. In the quartz of one class certain facets of the crystal were found on minute examination to lean all in one direction, — to the right, say, — whilst with the other class the corresponding facets leaned to the left. The first class was dextro-rotatory, the second lævo-rotatory. And had there been any doubts that rotatory power is due to structure, these must have been

removed by the consideration of the fact that the optical activity of a substance disappears when its crystalline structure is destroyed, as happens to quartz when it is fused, or to camphor when it is dissolved.

Crystalline structure may produce rotation, but *how* does it effect it? This is a question not easy to answer

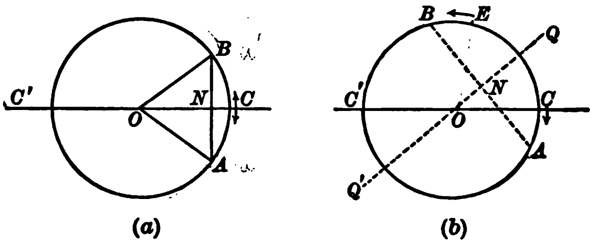


FIG. 25

satisfactorily, especially within the limits of such a lecture as this, but perhaps I may give you some glimpses of what has been done to solve the mystery. It is first necessary to realize that what looks like a *plane* polarized beam of light may really be a combination of two equal and opposite *circularly* polarized beams, the orbits of the two circles being described in opposite senses. Suppose that we set two particles off from C (Fig. 25 *a*) with equal speeds in opposite senses in the circle, one going round clockwise and the other counter-clockwise. After a time they will arrive at the points B and A respectively, where B is just as far above the level COC' as A is below it. Now if we raise a point a distance BN by means of one motion, and lower it an equal distance, AN, by means of the other, the effect of the combined motions is to keep the particle at the level N on the line COC'. Thus the combined effect of two equal and opposite *circular* motions is exactly equiva-

lent to a vibration along the *straight line* COC'; in other words, what looks like rectilinear (or plane) polarization may really consist of a combination of two opposite circular polarizations. Let us suppose, in the next place, that the two particles do not set out simultaneously from C, but that one starts from C and moves round the circle in a clockwise sense, while the other goes in the opposite sense, and starts from E (Fig. 25 *b*). It will be seen, as before, that the combination of these two motions is equivalent to a vibration along the straight line QOQ', which is such that OQ bisects the angle EOC. Think next of a right- and a left-handed circularly polarized wave moving through a crystal, and that, owing to the peculiar structure of the crystal, these two waves move through the crystal with different speeds. The two waves will take a different time to traverse a given thickness of the material, so that one will get through the plate faster than the other. A point in the left-handed wave (let us say) will, while the wave has traversed the plate, have made a certain number of complete revolutions and come back to its starting-point C (Fig. 25 *b*); the corresponding point in the other wave will have had more time when that wave emerges from the plate, and will have arrived at E. Once through the plate and into the surrounding non-crystalline medium, the two waves will proceed at equal speeds, so that their combined effect will correspond to that of two circular motions described in opposite senses at the same rate, one starting from C and the other from E. We have already seen that these two are equivalent to a vibration along a *straight line* $Q'OQ$, or to plane polarized light. However, the plane of polarization will now be $Q'OQ$, whereas it was $C'OC$ on entering the crystalline plate; in other words, the crystal will have

rotated the plane of polarization through an angle represented by COQ.

It remains only to consider what structure would give rise to different speeds for right- and left-handed waves. An almost endless variety of such structures might be suggested; almost anything would serve the purpose that would present a lack of symmetry to a clockwise and a counter-clockwise circular motion. Suppose that we could watch a crystal being built up, as it is when the solid slowly crystallizes out of the mother liquor. Each molecule, or group of molecules, when it fell down, would take up its place on the solid already formed, and it would do this not in a random fashion, but according to some definite rule, as if in obedience to some inexorable law of its being. Thus each group might be shaped somewhat as shown in Fig. 26, and the different groups piled on one another in the fashion there depicted. Under such circumstances the crystal would present a lack of symmetry as regards right- and left-handed rotation. It is easy to imagine a great variety of patterns that would be similarly unsymmetrical, and much ingenuity has been displayed in building up artificial media in some such way as this, and arranging them so as to endow the structure with optical rotatory power. Thus Reusch showed that by superposing thin films of mica according to a simple law, the rotatory power of quartz could be reproduced in all its details. More recently, under the

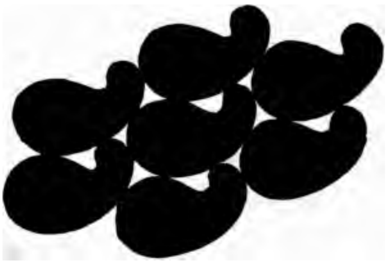


FIG. 26

guidance of the electric theory of matter, it has become common to estimate the influence, in rotating the plane of polarization, of groups of electrons arranged in an unsymmetrical manner. With certain simple assumptions it is possible to express the ideas in the exact language of mathematics, and so to test the theory in a *quantitative* way by seeing to what extent it agrees with the most careful measurements of rotation. There are two such tests of any theory: first, it must indicate the relation between the amount of rotation and the thickness of the medium that is traversed; and second, it must show in what way the rotation depends upon the color (or, in other words, the frequency) of the light. Any theory such as has been suggested above shows that whatever be the color of the incident light, the amount of rotation should be proportional to the thickness of the active substance through which the light passes, *i.e.* it should be twice as great for two inches as for one. The following table gives the rotation produced by two plates of quartz, one being 1 millimeter, and two others 7½ millimeters in thickness, the rotations being given in degrees for various colored lights:—

Thickness	Red	Orange	Yellow	Green	Blue	Indigo	Violet
1 mm. . . .	18	21½	24	29	31	36	42
7.5 mm. . . .	135	161¼	180	217½	232½	270	315

It will be observed that the amount of rotation with each color follows the law of proportionality to the thickness, just as the theory indicates. The theory also shows that the relation between the amount of rotation and the frequency of the vibrations in the light is, for a substance

like quartz, given by a formula of the type $R = af^2 + \frac{bf^2}{f^2 - f_1^2}$, when R is the rotation, f the frequency, and a, b, and f_1 are constants depending on the nature of the substance. How closely this fits the facts is shown in the following table, which compares the theoretical and the observed natures of R for the case of quartz, R denoting the rotation in degrees produced by a plate one millimeter in thickness, and f being the frequency in million millions per second: —

f	140.12	169.41	206.80	277.65	447.01	456.89	508.82	517.85	519.74
R (theory) . .	1.57	2.29	3.43	6.23	16.56	17.33	21.70	22.53	22.70
R (observation)	1.60	2.28	3.43	6.18	16.54	17.31	21.72	22.55	22.72
f	549.09	589.57	609.92	624.70	687.97	740.98	871.53	1091.7	1367.1
R (theory) . .	25.51	29.67	31.92	33.60	41.46	48.85	70.61	121.34	220.57
R (observation)	25.53	29.72	31.97	33.67	41.55	48.93	70.59	121.06	220.72

So far we have been dealing with substances that lose their rotatory power when they are brought into a liquid state by fusion or solution. There exists, however, a large number of substances that have this power although they are liquids, and that retain it even when the liquid is turned into a vapor. Thus, in 1815, Biot discovered that turpentine is optically active, this important discovery, like several others in science, being accidental, as it was made when Biot was searching for something quite different. Two years later the same physicist made a discovery that is still more interesting from our point of view. He looked for rotatory power in the *vapor* of turpentine, and actually observed it. His most conclusive results were obtained when working with vapor in a tube about fifty feet long, set

up in an old church at Luxembourg. However, although he saw clearly that there was rotation of the plane of polarization of the light that had passed through this tube, he was prevented from *measuring* it accurately, as the inflammable vapor ignited and destroyed his apparatus. Science had to wait nearly half a century until the investigation was resumed in 1864 by Gernez. He succeeded in determining the rotations produced by various liquids and in showing that their rotatory power is retained when they are transformed into the state of vapor. This is a very striking result, in view of what has been said as to the probable explanation of optical activity. This power has been ascribed to structural arrangement, and yet there seems no possibility of permanent structure with the molecules of a vapor which are in constant motion. This seems to drive us to the hypothesis of structure not *of* the molecules, but *in* the molecules themselves. The atoms of which the molecules are built may be arranged in such a way as to produce optical activity, so that the study of our subject lures us into the rich and expansive field of *Stereo-chemistry*. This is that fruitful department of modern chemistry that concerns itself with the arrangement of atoms in space and seeks to determine how, if you were making a model of a molecule, you would place the different atoms of which it is composed. We have time only for a hurried glance into this field, enough perhaps to stimulate our desire for further knowledge and to break down a portion of the arbitrary boundary that has been set up between chemistry and physics.

The first epoch-making work in the direction that has just been indicated was that of Pasteur, who, in 1848, took p the study of the rotatory power of different forms of

tartaric acid. He found it possible to separate this acid into four different classes, all with the same chemical constitution (*i.e.* made up of the same elements), but with different physical structure and different optical power. Two of the classes were optically inactive, and two had rotatory power. One of the inactive acids had the peculiarity that when it was crystallized, its crystals, on careful examination, proved to be separable into two distinct types, whereas, with the other inactive acid, the crystals were not thus separable. The two types of crystals that have just been mentioned as constituting together the inactive acid of the first class, differed from one another in a simple yet remarkable manner. Their points of resemblance and of contrast were exactly like those of certain objects and their images as seen in a plane mirror. Your right and left hand have many points of likeness, but yet they are quite different. They are not superposable; twist the right hand as you will, and it refuses to fit into a glove made for the left. If you hold the right hand before a mirror, and look at the *image*, you will see a left hand, so that the relation between the two types of crystals under discussion might be indicated by saying that one type was left-handed and the other right-handed. Pasteur, after separating these types from one another, formed a solution of each. The right-handed type was found to have the same chemical constitution as the original acid of which it formed a part; *but instead of being inactive, it had rotatory power.* It rotated the plane of polarization, let us say, to the right, and so was *dextro*-rotatory. The left-handed type had also the same chemical constitution, but it, too, was optically active and *lævo*-rotatory. The presence of equal quantities of these two types in the original acid explained its inactivity,

for each neutralized the other, the right-handed rotation produced by the first type being exactly counterbalanced by the left-handed rotation of the second. From the consideration of these and similar phenomena, Pasteur was led to make the general statement that all organic compounds could be divided into one or other of two groups, according to the form of their molecular arrangement. It will be observed that not every object differs in appearance from its image in a plane mirror; in the case of a perfectly regular figure, such as a cube or a regular tetrahedron, object and image are superposable. On the other hand, with such objects as a screw, an irregular tetrahedron, or the hand, object and image are not superposable. Pasteur suggested that when the arrangement of the atoms fell into the first of these classes there would be molecular symmetry, and the substance would be optically inactive; but a group belonging to the second class would represent molecular asymmetry, and rotatory power would be expected.

After Pasteur's researches, the next great impetus to work in this field was given in 1874 by the speculations of Van't Hoff and Le Bel. The fundamental conception here was a definite arrangement of atoms, the so-called *tetrahedral* molecule, which has formed the basis of the larger part of later speculations in stereochemistry. It is now a commonplace of the text-books, and it would be out of place to discuss it here further than is necessary to give a general impression of the main ideas, in so far as they throw any light on the problem of optical activity. We have already remarked that the fundamental idea of stereochemistry is that, in a given compound, the atoms composing a molecule are arranged in a definite form, and the fundamental problem is to determine that form for

different compounds. Now Van't Hoff's hypothesis is that, in the case of organic compounds, the arrangement is such that the different atoms, or groups of atoms, occupy the four corners *ABCD* (Fig. 27) of a tetrahedron, the carbon element being in the center. If this were so, it would be convenient to separate carbon compounds into two classes, in the first of which there is only one carbon atom present, and in the second there are two or more such atoms. In the first class, if the four groups at the corners of the tetrahedron were all different, any arrangement and its optical image would be different. Thus every form would have its associate, and as each would be unsymmetrical, they would both be optically active, one rotating to the right and the other to the left. A compound made up of equal parts of these two forms would be neutral, and so optically inactive. Hence in this class we should expect three modifications of any arrangement: one dextro-rotatory, another lævo-rotatory, the third inactive. In the second class, where there were more than one asymmetric carbon atom in the molecule, the number of possibilities would be greater. The case of tartaric acid has already been described. Here we have four different forms — one dextro-rotatory, another lævo-rotatory, a third inactive, being compounded of equal proportions of the first two, and a fourth also inactive, but for a different reason. This inactive form differs from the other in that it cannot be resolved into active constituents. The molecule is built up of two similar halves, so that there is optical compensation *within the molecule itself.*

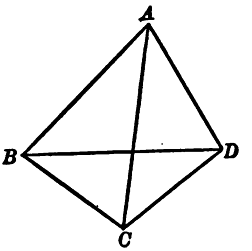


Fig. 27

A great deal of work has been done in this field since 1874, and there has been much to give support to the main lines of the theory here set forth. It has been found that there is no rotatory power in any compound that does not contain an asymmetric carbon atom, and that by introducing or removing such atoms from a substance the power of optical activity can be made to come or go. Many of the difficulties that early presented themselves have been removed. Thus, at the outset, several substances that contain an asymmetric carbon atom were found to be inactive, contrary to the theory; but later research has shown either that such substances really possess some rotatory power (although a feeble one), or that they consist of mixtures in equal quantities of two oppositely rotating constituents, or that they are made up of two similarly constituted halves, which, although not separable, have oppositely rotating powers. Of special importance in this domain have been the researches of E. Fischer on the members of the sugar group. If Van't Hoff's hypothesis be right, then it is a simple problem of permutations and combinations to predict the number of different modifications that should be possible with a given group of atoms. If the mathematical problem be too hard or too repellent, you may reach the answer by the aid of models and a little patient trial. You have merely to attach a series of differently colored balls to the corners of a tetrahedron, and see how many different arrangements it is possible to make. In doing this you may learn more than the mere number of different forms in which the compound could exist, for, by observing the salient points of resemblance and contrast between different arrangements, you may get hints as to the significance of these for chemistry and for optics. Thus, when Fischer was working on

the members of the sugar group, he made a careful examination of dextrose, and concluded from its chemical reactions that the atoms in the molecule were arranged in a certain way. The arrangement was not symmetrical, and the substance was optically active of the right-handed rotatory type. Fischer concluded that there might be expected to exist another form, the arrangement of whose atoms would be related to that just mentioned in the same way as an object and its image in a mirror. He succeeded, after careful trial, in actually isolating such a form, one that was also optically active, but of the left-handed rotatory type.

Perhaps enough has been said to indicate that the hypothesis of a definite arrangement of the atoms in the molecules of a substance is not a mere idle speculation. It has proved a very useful conception in modern chemistry, but our interest in it here is mainly for the light it throws on the problem of optical activity. We have seen that rotatory power is always associated with an *asymmetrical* arrangement of the atoms, and when dealing earlier with quartz and similar active solids, we remarked that lack of symmetry would result in right- and left-handed circularly polarized waves traversing the medium with different speeds, and so would account for the rotation of the plane of polarization.

Apart, however, from all such speculations, it may be well to remark that there is no doubt about the fact of rotation, so that, whether these theories find favor or not, we may make use of this fact in any way that seems good to us. The facts that are simplest and most important to bear in mind are as follows: Not every substance is optically active, but many possess this power of rotating the plane of polarization of a beam of light that passes

through them. The amount of the rotation is found to depend on the temperature, and also on the color of the light that is employed. For light of a definite color (*e.g.* that of one of the sodium lines), the rotation varies directly as the thickness of the substance traversed by the light. In the case of liquids it depends also very markedly on the *strength* of the solution, and this has given rise to a very simple and very important plan for estimating the strength of a given solution. It could be carried out with the apparatus used in the experiment with which this lecture was begun. Let light from a sodium flame pass through the first of these Nicol's prisms. It issues, as we have seen, as plane polarized light, and we can determine the plane of polarization exactly by noting the position in which the second Nicol must be placed in order to cut off all the light from the screen. Now put a vessel containing an optically active solution between the Nicols, and you will find that the second Nicol must be turned through a certain angle in order once more to completely cut off the light from the screen. If you have a means of measuring carefully the angle through which the Nicol was turned, you know exactly the rotation of the plane of polarization that this solution has produced. If, then, by previous experiment, you have determined the strength of solution that produces that amount of rotation, you realize that your problem is solved. I have suggested the use of Nicols, but of course other means of producing polarization may be employed. A great variety of polarizing apparatus has been invented and is constantly being used to determine the strengths of solutions of such substances as nicotine, cocaine, starch, and alcohol, and most important of all, considering the magnitude of the commercial interests involved, of sugar.

It may seem a curious ending to a lecture that deals entirely with what seems almost painfully "unpractical," — polarization, rotatory power, molecular structure, and the like, — to refer to means of measuring the strength of alcohol or the value of a cargo of sugar. If, however, you know anything of the history of science, you will not think it strange at all, but will rather be inclined to regard it as typical of almost countless similar cases. No wise man would undertake to draw quite clearly the line between "practical" and "unpractical," between "useful" and "useless," knowledge. By all means let us be practical and useful, but let us use these terms in no narrow sense, nor suppose for a moment that the race will advance most rapidly, even with material things, by sticking closely to what is obviously "practical." If our ancestors had always been sticklers for "practical" knowledge, we should probably still be eating acorns.

VI

THE LAWS OF REFLECTION AND REFRACTION

In the opening lecture of this course it was remarked that man's knowledge of optical laws might be summed up almost to Newton's day within the compass of a single sentence. Of general principles all that was known was the fact and the law of reflection (as regards direction only), the fact of total reflection, and the fact of refraction. It is difficult for any but a specialist to realize what enormous advances have been made since then, both in observation and in theory. We now have a great variety of instruments of precision that enable us to observe most optical phenomena with marvellous accuracy, and a theory has been developed that enables us to group together the whole mass of facts with the utmost simplicity and with almost startling success. Few men are in a position to understand the searching nature of the test that can now be applied to optical theories, and to appreciate how well the modern theory stands the test. Not until you have put yourself in such a position can you understand the confidence of a modern physicist in his theories. He is no longer content with a mere descriptive theory which tells him in a general way that such and such phenomena are to be expected. His theory must enter into the minutest details and predict *quantitatively*. It must tell him that if he measures this or that with sufficient accuracy, he will find its measure to be so and so. In the case of the modern theory of light,

all the improvements and all the refinements of modern instruments but tend to confirm the correctness of the prediction. I have already given you instances of this (for example, when dealing with dispersion); but, even at the risk of wearying you with figures and with tables, I must give you more of a similar kind to-night and in later lectures.

Let us look first at the simpler and more generally known laws of reflection and refraction. These deal only with the *directions* of the various rays, and show how to determine the directions of the reflected and refracted ray of light when that of the incident ray is given. In Fig. 28 AB represents an incident ray which strikes a reflecting surface BK at the point B, in such a way that part of the light is reflected along the ray BC, and the rest refracted along BH. If EBF be drawn at right angles to the reflecting surface, the plane containing AB and BE is called the plane of incidence. The law of reflection, which determines the direction of the reflected ray, states that BC is in the plane of incidence and that the angle EBC is exactly equal to the angle EBA, or $r = i$, with the notation indicated in the figure. The law of refraction (sometimes called Snell's law, having first been laid down by Snell in 1621) states that the refracted ray BH is also in the plane of incidence, and that the angle FBH is connected with the angle ABE by the relation $\sin i = \mu \sin r'$, where μ is a constant depending on the nature of the two media on each side of

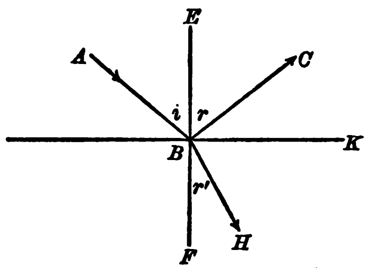


FIG. 28

BK, and known as the relative *refractive index* of these media. (If the space above BK is a vacuum, then μ is the absolute refractive index, or simply the refractive index of the medium below BK.) As it is impossible to find an angle whose sine is greater than unity, Snell's law shows that r' could not be found if the angle of incidence i were such that sin i were greater than μ, the relative refractive index. If the first medium be more highly refractive than the second, for example, if the first be water and the second air, then the relative refractive index μ is less than unity, and the angle whose sine is equal to μ is called the critical angle. Under such circumstances r' would be impossible if the angle of incidence i were greater than the critical angle — so that we should expect that there would be no refracted ray, and that all the light would be reflected. This is the phenomenon of *total reflection* that was brought before your notice in the first lecture, and the point to be noticed now is that Snell's law indicates exactly the conditions under which this phenomenon is to be expected.

All these laws with reference to reflection, refraction, and total reflection have been verified experimentally with the greatest precision. Of all the countless experiments that have been made with reflected beams, no careful measurement has ever suggested the slightest departure from the law of equal angles, $i = r$. And the same may be said of Snell's law of refraction. Of course there is a possible error in all such measurements, for no amount of care can make them absolutely exact. A considerable part of modern science consists in estimating carefully the *probable* errors of measurement. To test these laws of reflection and refraction, it is necessary to measure certain angles, and this, with the wonderful instruments of

to-day, can be done with great nicety, though of course not with absolute precision. With very great care the angles may be measured accurately enough to insure the correctness of refractive indices to six places of decimals; but even with the care and skill necessary to insure this degree of accuracy, no one has found any departure from Snell's law that was outside the limits of the probable errors of experiment.

It will have been observed that these laws of reflection and refraction are merely condensed statements of experimental facts. No theory is involved in them; they simply sum up in a convenient form the results of a large number of observations and so serve one of the great ends of science — to save labor and relieve our memories of the burden of too many isolated facts. If, however, we are imbued with the scientific spirit, we cannot rest content with such laws, but must strive to fit them in with our other knowledge and to get a view of optics that is comprehensive enough to take in these laws and all else within the optical field besides. To this end we need a theory of light, and for about a century there has been little doubt as to the general lines along which such a theory must be developed. We need a *wave theory* of some kind, that is, we must think of light as due to a periodic disturbance like a wave propagated in a medium. Now, if we set out with any such wave theory, and with the conception that a wave travels with a definite speed in one medium (such as air), and with a different speed in another (such as glass), we are led simply and inevitably to just these laws of reflection and refraction of which we have been speaking. These laws are required to secure continuity at the interface between two media; without them there would be a rupture there or a sudden

break. At present I cannot stop to prove such a statement, although it is very easily proved; I must simply ask you to believe that it is so, and that the relative refractive index of which we have spoken is the ratio of the speeds of the waves in the two media under consideration.

As far, then, as the mere *directions* of the reflected and refracted rays are concerned, almost any wave theory will account for the facts. But other things than these directions must be considered. Suppose that you are studying the effect of waves that you see running across the surface of a lake. You may well want to know more than the mere direction in which they are moving. If you wish to estimate the damage that the waves will do when they strike upon some object, you will want to know their *height*. In an ether wave which, according to our theory, gives us the sensation of light, each element of the ether vibrates to and fro about some mean position. Its greatest displacement from this position corresponds exactly to the height in a water wave, and is technically known as the *amplitude* of the wave. This you will wish to know if you are to measure the intensity of the light, for it may be proved that the intensity depends on the amplitude, and is, in fact, proportional to the square of this amplitude. Another important element in a wave of water, or of anything else, is its *phase*. Watch two waves, similar in height and shape, running side by side along the surface of some water. The crest of one may always be in line with the crest of the other. In this case they could be described as being "in phase," or "in the same phase." More probably, however, the crest of one would lag somewhat behind that of the other. To describe this we should say that there was a "difference of phase" between the waves, and this difference might be

a matter of much import. (As a matter of fact, it would have great importance if we came to consider the effect of combining the two waves, as we shall see in the next lecture on Interference.) What, then, does a wave theory of light tell us of the amplitude (or intensity) and the phase of the reflected and of the refracted beams, and how do the predictions of theory compare with the results of observation? These are very important questions. They are, indeed, crucial in optical theory, for they enable us to distinguish one wave theory from another, and to say which best fits the facts. This, of course, settles the question as to which theory is to be preferred, for the whole end of a scientific theory is to fit the facts; if it fails to do this, it is probably worse than useless. What, however, do we mean by distinguishing one wave theory from another? Any theory of light that endeavors to coördinate its phenomena by means of the conception of a to-and-fro motion propagated in the ether may be called a wave theory; but before such a theory can lead us to precise results, we must formulate definite ideas as to the nature of the ether. Here there is room for difference of opinion, and so for different wave theories. In any case the idea of an ether is an *abstraction;* it is reached by taking away certain properties of ordinary matter and endowing an ideal medium with all that remains. Without such a process the ether could not be thought of at all, for our mental conceptions are necessarily derived, more or less directly, from our experience. Such *abstract* ideas are common enough in scientific and even in ordinary discussion. Thus we have the idea of an *incompressible* substance. We observe that air is easily compressed, that bread resists compression more strongly, and that water opposes with tremendous force any attempt to diminish its

volume. It is an easy matter *in thought* to carry on the process until we have abstracted completely the power of yielding to compression, and so we reach the abstract idea of an incompressible substance. If we were interested in considering the motion of such a substance, we might well apply accepted dynamical principles to aid us in the discussion, and so we might reason as to its behavior, even although it would be impossible actually to point to a substance that was incompressible. Again, we have the idea of a *frictionless* fluid. We observe that if we pull a spoon through treacle, the treacle resists the motion, and we have to exercise a considerable force to overcome this resistance, or friction. If we replace the treacle by olive oil, the friction is diminished, while with water it is scarcely perceptible. Here, again, it is not difficult to abstract the viscosity, the power of opposing motion by friction, and so to arrive at the abstract idea of a frictionless fluid. In this case, also, we might apply dynamical principles to aid us in discussing the behavior of such a fluid, and we need not be hampered in that discussion by the fact that no one has ever presented us with a bottle of a frictionless fluid. Now the ether that is spoken of so much in these latter days in various branches of science is a similar abstraction. Let us begin with ordinary matter, a piece of steel or jelly, say. It has a definite density, and definite elastic constants which measure its powers of resistance. It resists a change of volume; it requires force to compress or expand it. It resists attempts to twist it and change its shape. Such powers of resistance can be measured on a definite scale and expressed numerically by means of such elastic constants as compressibility and torsional rigidity. It seems natural in a wave theory of light to begin with an ether that has all

these powers, and to see if, by a proper choice of the constants representing density, compressibility, and rigidity, it is possible to account for the phenomena of light. This is the famous *elastic solid theory* of light. If a disturbance is set up in a medium such as has been described, it is easy to show that waves will be propagated with a speed that will depend on the magnitude of the elastic constants. Moreover, in passing from one medium to another with different elastic constants, reflected and refracted waves will be set up, and, as has been indicated already, the *directions* of these will correspond exactly to those laid down by the laws of reflection and refraction that have already been formulated and have been fully verified by experiment. It would thus appear that we are on the right track; but when we come to look carefully at the other features of the waves, their amplitudes and phases, we begin to encounter difficulties. There are other difficulties that I need not refer to; it will be sufficient to say that the only successful way of overcoming them all is to *abstract* something from our ordinary elastic medium. We have too much cargo and must lighten the ship. Let us throw over all power of resisting change of shape, except the power of resisting a twist. The medium so obtained will possess the mobility of a fluid with some of the rigidity of a solid. As it does not resist a mere change of shape, it will allow bodies to move freely through it like a fluid; but it objects to twisting of its elements, and so has rigidity. A fluid like water, with a number of little gyrostats spinning in it, and by their momentum opposing any change of spin, might serve as a rough model to bring to mind the peculiar properties of this "rotationally elastic" ether. It might be impossible to construct this model, but there is no great difficulty in

conceiving of such a medium by the process of abstraction and of reasoning as to its behavior in obedience to general dynamical laws. Such a medium, if disturbed, will transmit the disturbance as a wave (*i.e.* a periodic displacement), and this wave will not be of the longitudinal type, but of the transverse kind that the phenomenon of polarization demands from any theory of light. The speed with which the wave travels will depend on the rigidity and the density of the ether, and the ratio of the constants representing these quantities must be chosen so as to fit in with the observed value of the speed of light in vacuo where there is nothing but ether to affect the speed. The presence of matter will modify the effective rigidity, so that a wave will travel with a different speed in water or glass than in vacuo. In passing from one of these media to the other, there will be reflection and refraction, and provided that we assume that there is no discontinuity of motion at the interface, no rupture at the surface of separation, the general principles of dynamics will enable us to calculate not only the directions of the reflected and refracted waves, but also their amplitudes and phases. When this is done, it becomes at once evident that the condition of the reflected and refracted waves must depend on the state of polarization, as well as on the direction, of the incident beam. Two important cases present themselves: in one the light is polarized parallel to the plane of incidence, and in the other at right angles to this plane — these cases being specially important, as the details of all other cases can be immediately deduced from a consideration of these two. Then it also appears, as might be expected, that the results depend on the nature of the transition from one medium to the other, from air to water, say. In any case, actually presented in an experiment, this tran-

sition may be absolutely sudden, or it may be more or less gradual. Such a question cannot be decided offhand; to the eye the transition may look quite sudden, but this effect may be due to imperfections of our vision, and if we could see things at close enough range, the idea of an absolutely sudden transition might appear illusory. However, the hypothesis of a sudden transition is probably the natural one with which to begin, and it was on this hypothesis that formulæ from which to calculate all the details of the reflected and refracted waves were first obtained. In the present course I have promised to eschew mathematics as much as possible, so that here we must be content with a graphical representation of the formulæ. Instead of looking at all the details, let us for a time concentrate our attention on a single one, the intensity of the reflected beam — a quantity, as has been remarked, that is proportional to the square of the amplitude of the reflected wave. In Fig. 29 the curves marked R and R' represent the percentage of the incident light reflected from glass, whose refractive index is $\mu = 1.52$, at different angles of incidence i. The different angles of incidence are indicated by distances measured across the page, and the corresponding percentage of reflected light by distances at right angles to this. Both curves represent the formulæ obtained from theory in the manner just indicated, R' dealing with light polarized parallel to the plane of incidence, and R perpendicular thereto. It is specially worthy of remark that for the latter case the intensity begins to diminish as the angle of incidence (i) increases, that it goes to zero at the point marked P, and then rapidly rises. The theory indicates that the position of the point P is determined by the simple formula $\tan i = \mu$. At this angle none of the light that is polarized

perpendicularly to the plane of incidence is reflected, so that all the light that can be reflected at that angle is polarized *parallel* to the plane of incidence. This indicates

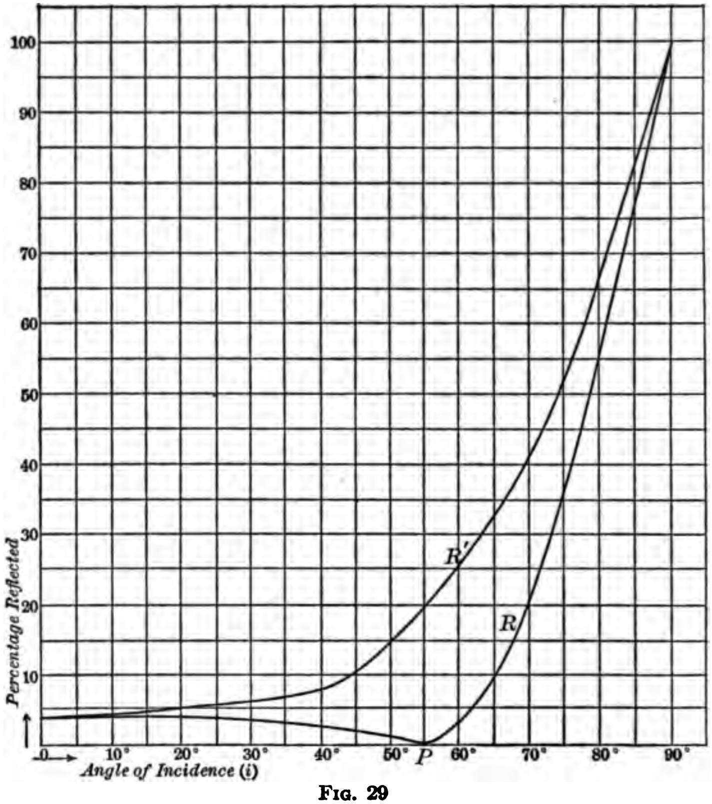


FIG. 29

that by simple reflection we have a means of producing plane polarized light. We have merely to arrange that light should fall on a reflecting surface at the proper angle. This angle is given by the formula $\tan i = \mu$, and is called

the *polarizing angle.* It is just about a century since Malus discovered that light could be polarized by reflection, and a few years later Brewster deduced from a series of experiments that the polarizing angle was given by the formula $\tan i = \mu$. The following table shows how the values of the polarizing angles of different substances, calculated from the theoretical formula $\tan i = \mu$, agree or disagree with the angles actually observed:—

i (theory) . .	53° 7′	53° 18′	55° 33′	55° 37′	58° 13′	58° 36′
i (experiment) .	53° 7′	53° 18′	55° 33′	55° 37′	58° 12′	58° 36′
i (theory) . .	59° 41′	60° 30′	63° 33′	67° 7′	67° 32′	67° 40′
i (experiment) .	59° 44′	60° 30′	63° 34′	67° 6′	67° 26′	67° 30′

It will be seen that the agreement is very close, but not perfect, and we should find results of the same character if we compared the theoretical and observed values of the intensity of the reflected light, and, what are much more readily measured with precision, certain phase relations. In all cases the theory fits the facts very nearly, but not exactly. We find, however, that all these minute discrepancies disappear when we abandon the hypothesis of an abrupt transition from one medium to another. A comparison of theory and experiment then gives us the means of estimating approximately the thickness of the surface layer within which the transition takes place. We find in many cases that it is less than one-hundredth of a wave length, and how extremely short that is for ordinary light will be made apparent in a later lecture. Let us see how well our theory fits the facts when we take into account the influence of

this transition layer. We shall consider first the intensity of the reflected light, although the intensity cannot be measured so accurately as most of the other features with which we have to deal. It is true that there has been a great improvement in photometric processes of recent years, but these are still far from the stage of precision that has been attained in other departments of optics. The following table gives the percentage of the light reflected at different angles of incidence (i), calculated from theory for the case of glass, and compares the results with the most careful observations of the amount of light actually reflected:—

i	0	10°	20°	30°	40°
Percentage Reflected (theory) . .	3.78	3.78	3.90	3.92	4.39
Percentage Reflected (experiment)	3.78	3.78	3.77	3.92	4.37

i	50°	60°	65°	70°
Percentage Reflected (theory) . .	5.37	8.31	11.28	16.12
Percentage Reflected (experiment)	5.53	8.34	11.16	16.04

Some of you, who find numbers distasteful or hard to comprehend, may prefer to see these results exhibited in a form that appeals to the eye. For this purpose they are exhibited graphically in Fig. 30. As we shall have quite a number of similar figures before our course is run, it may be well to adopt a uniform mode of presentation and explain it once for all here. You should bear in mind, then, that in all such figures, the *continuous curve corresponds to the redictions of theory, while the crosses indicate the results f actual experiment.* Thus the agreement or disagreement

between theory and observation is measured by the degree of closeness with which the crosses lie along the continuous curve. In this case it will be observed that the agreement

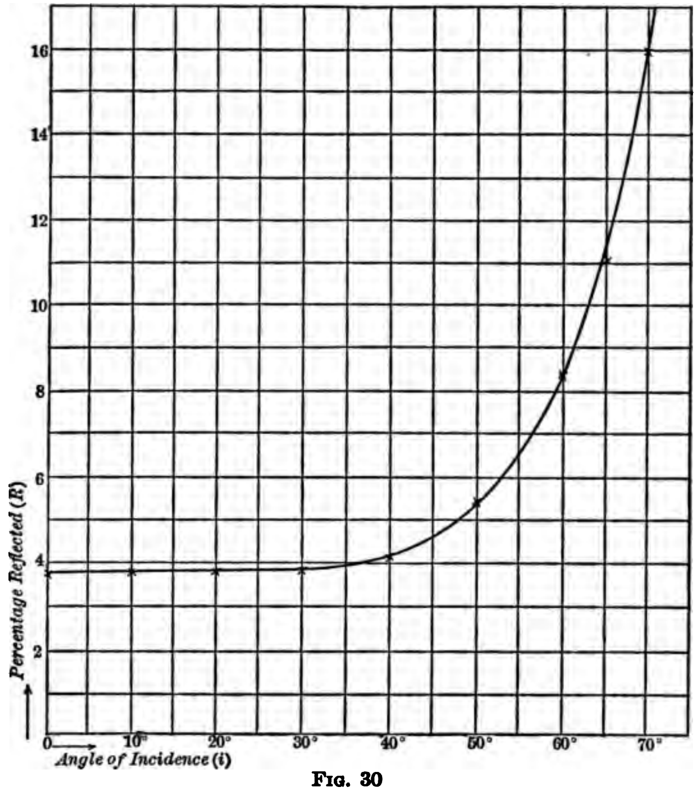


FIG. 30

is very close, especially in the region where the incidence is small, in which accurate measurements are most easily made. An inspection of the figure will show that, in the case of the most marked disagreement, it is more probable that the measure of intensity was rather too high, or too low, than that

the theory is in error. In nearly all cases the differences between theory and observation are well within the limits of the probable errors of experiment.

So much for the intensity of the reflected light. Next, let us suppose that matters are so arranged that the incident light has equal intensities when polarized parallel and perpendicularly to the plane of incidence, and let us measure the ratio of the intensity of the reflected light that is polarized perpendicularly to the plane of incidence to that of the reflected light that is polarized parallel to this plane. The measurement of this *ratio* can be made far more accurately than that of the intensity of any light. Its value can be obtained without any photometric processes at all, simply by ascertaining the position of the plane of polarization of the reflected light, and the measurement of the angle determining this position is an operation that can be performed with great delicacy. The table that follows gives us the means of comparing the values of this ratio in the case of reflection from diamond at various angles of incidence and of estimating the degree of accuracy with which the theory fits the facts:—

i	60°	61°	62°	63°	64°	65°
Ratio (theory) . .	.0421	.0324	0234	.0166	.0104	.0056
Ratio (experiment) .	.0420	.0312	.0213	.0178	.0102	.0057

i	66°	67°	67° 30′	68°	68° 30′	69°
Ratio (theory) . .	.0028	.0009	.0006	.0007	.0013	.0020
Ratio (experiment) .	.0030	.0009	.0006	.0007	.0013	.0026

i	70°	71°	72°	73°	74°	75°
Ratio (theory) . .	.0049	.0103	.0177	.0275	.0399	.0552
Ratio (experiment) .	.0054	.0106	.0184	.0296	.0469	.0576

The graphical representation of these results is exhibited in Fig. 31, and from either the figure or the table it will be seen that the agreement between theory and observation is extremely satisfactory.

Another quantity that is capable of very accurate measurement is the difference of phase between the two reflected

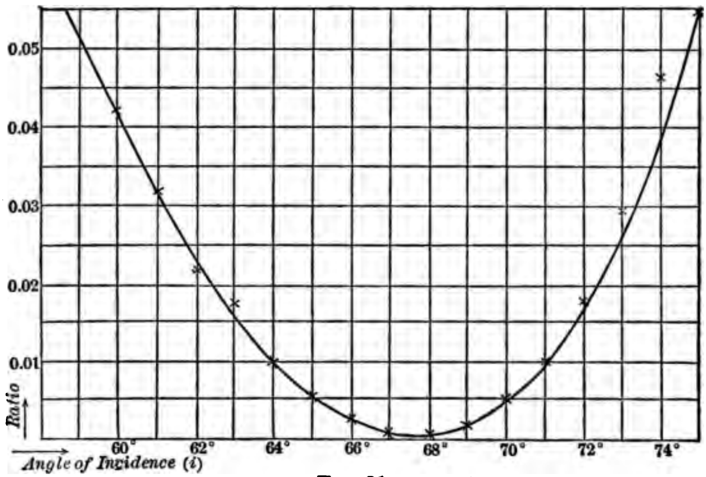


FIG. 31

waves when one is polarized parallel and the other perpendicularly to the plane of incidence. The results for diamond are shown in Fig. 32, the difference of phase being expressed as a decimal fraction of a wave length, so that for a difference marked 0.5 one wave is half a wave length behind the other, and thus the crest of the first is in line with the hollow of the second. It was pointed out earlier in this lecture that, on the theory of an absolutely abrupt transition from one medium to another, the polarizing angle would be given by the formula tan $i = \mu$, and a table was

made out which showed that this is very nearly true for most of the substances referred to. The examination of the influence of a thin surface layer of transition on the position of the polarizing angle shows that the layer should affect this angle very slightly, and that it might either increase or decrease it, according to the nature of the layer.

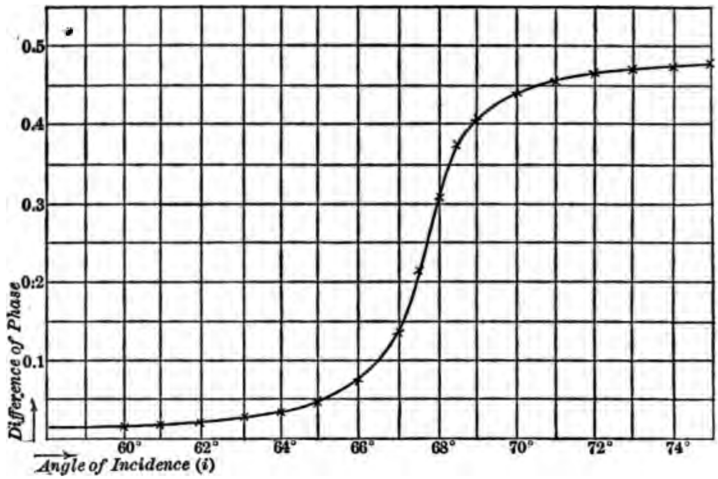


Fig. 32

In the case of a certain specimen of glass, for which the theory of the transition layer predicted a polarizing angle of 56° 23′ 38″, the mean of a most careful series of experiments fixed this angle at 56° 23′ 30″.

Theory also shows that if the first of the two media in contact with one another have a higher refractive index than the second, the whole of the light will be reflected when the angle of incidence is greater than the critical angle. This is the phenomenon of total reflection already referred to, and here, as elsewhere, the agreement between theory

and observation is as close as could be desired. The following table and Fig. 33 set out a comparison between theory and experiment for the difference of phase (Δ) between two waves that are totally reflected, one being

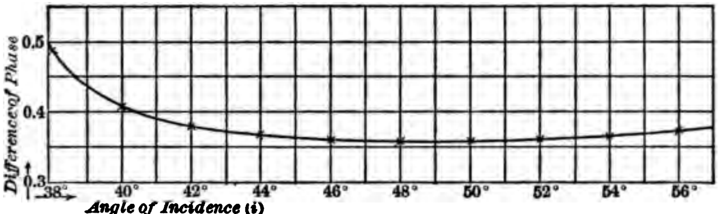


FIG. 33

polarized parallel and the other perpendicular to the plane of incidence. The differences of phase are expressed as decimal fractions of the wave length, and, as before, i denotes the angle of incidence. The substance dealt with experimentally had a refractive index, $\mu = 1.619$, and a critical angle of 38° 9′.

i	38° 13′	39° 58′	41° 59′	44° 2′	46° 4′
Δ (theory)	.488	.457	.379	.364	.358
Δ (experiment) . . .	.489	.457	.377	.364	.359
i	47° 54′	49° 58′	51° 57′	53° 58′	55° 57′
Δ (theory)	.356	.356	.360	.363	.368
Δ (experiment) . . .	.356	.357	.360	.363	.365

All these tables and figures have reference to reflection from transparent, non-crystalline substances. If the reflector be a crystal, or if it be more or less opaque, theory

and experiment agree in showing that the laws of reflection may be considerably modified. The phenomena with crystals will be dealt with in a later lecture, but we shall

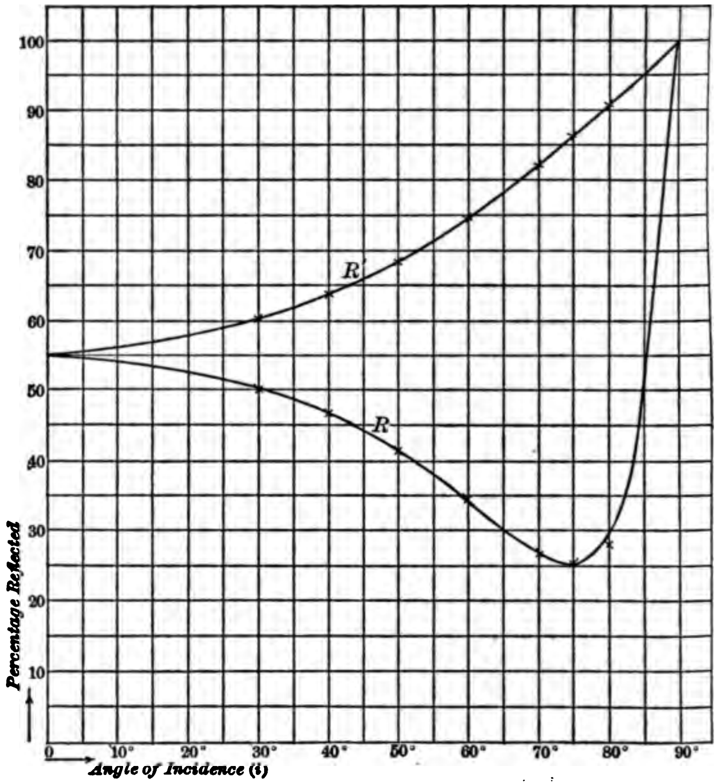


FIG. 34

not have time for more than a passing reference to the laws of reflection from opaque substances, such as metals. In this case what corresponds to the refracted wave is absorbed by the metal, but theory enables us to predict all the details

of the reflected beam. The laws are more complex, but the general character of the results has some resemblance to that for transparent reflectors. This will be made evident by a comparison of Figs. 29 and 34, which represent corresponding quantities for glass and steel. It will be

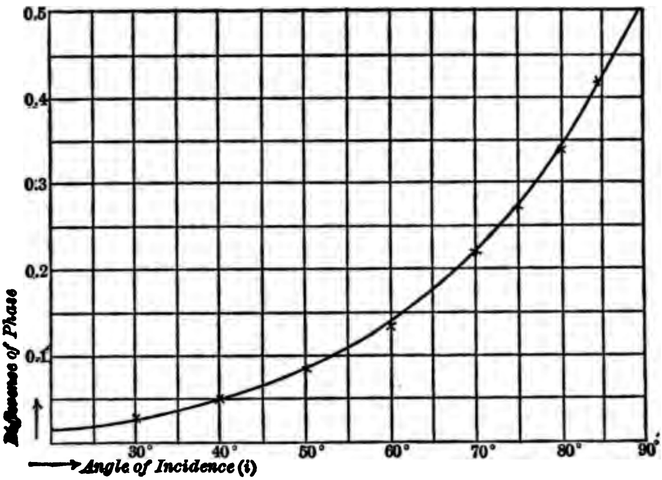


FIG. 35

observed that in both cases for light polarized parallel to the plane of incidence the intensity of the reflected beam increases steadily with the incidence. With light polarized perpendicularly to the plane of incidence, the intensity in both cases begins by diminishing, reaches a minimum, and then increases rapidly. The main difference is that the amount of light reflected at normal incidence is very much greater for the metal than for the transparent substance, and that even at the angle where the reflection from the metal is a minimum (called the *quasi-polarizing angle* from its resemblance to the polarizing angle of a transparent

medium), there is still a considerable quantity of light reflected from the metallic surface. The difference of phase between the two reflected waves is represented graphically in Fig. 35 for the case of reflection from gold. This figure should be compared with Fig. 32, which is the corresponding figure for the case of reflection from a transparent substance. It will be seen that in all cases the crosses lie closely along the curves, indicating on all points an excellent agreement between theory and observation. The numbers corresponding to these figures are set out in the following table:—

i	R (THEORY)	R (EXPERIMENT)	R' (THEORY)	R' (EXPERIMENT)	Δ (THEORY)	Δ (EXPERIMENT)
30°	50.5	50.1	60.4	60.7	.028	.032
40°	46.5	46.2	64.0	64.2	.052	.056
50°	41.0	41.0	68.9	69.4	.088	.088
60°	33.9	34.1	74.8	74.5	.135	.130
70°	26.7	26.5	82.1	82.3	.211	.210
75°	25.4	25.5	86.1	86.1	.265	.265
80°	29.5	27.5	90.4	90.3	.331	.324

I hope that by this time enough has been said to show you that modern optical theory gives a completely satisfactory account of reflection and refraction, telling us all that we can want to know with the utmost precision, and agreeing in its predictions on every point with the most accurate measurements of the best experimenters. We may thus feel that we have our feet on solid ground when we set out to apply this theory to aid us in the solution of any problem that may present itself. In the time that remains of this lecture I wish to speak mainly of the application of the

laws of reflection and refraction to the design and construction of optical instruments. Clearly, if I am to do this at all effectively, I must limit myself strictly. The number and variety of optical instruments is enormous, and it requires not a little thinking to suggest many instruments of great precision that do not involve some optical principle. Optics has been called the "directing science" of modern times, because the principles that have been developed in its study have formed the basis of many of the most far-reaching speculations in modern science. It deserves the name perhaps even more truly for another reason. The advancement of science depends largely on the precision with which its researches can be conducted. Optical principles enter into nearly all instruments of precision, and thus the whole army of science is interested in these principles, and should realize that it is under a deep obligation to those men who have established them so firmly.

The laws of reflection and refraction that are most frequently made use of in the design of optical instruments are those simpler ones that deal with the *directions* of the rays. These laws have already been stated and discussed, but perhaps you will bear with me if I call your attention to a different mode in which they may be presented. We have seen that if a ray of light proceeding from A (Fig. 36), strike a surface BC so as to be reflected to E, the lines AB and BE will be equally inclined to the reflecting surface. Suppose, now, that we endow a ray of light with intelligence, and set it this problem: to start from A, strike the reflecting surface somewhere, and be reflected to E, and to *choose its path so that it will reach E as quickly as possible.* If you have any skill in elementary geometry, you will be able to prove that B, the point of striking the reflector,

must be chosen so that AB and BE make equal angles with BC; in other words, the law of reflection must be obeyed. Similarly, if you take the corresponding problem in refraction, and ask the ray to set out from A (Fig. 36), be refracted into another medium, and reach a point E in the shortest possible time, you will find that here, again, the law of refraction will have to be obeyed. In both cases you can prove the statements by showing that the time of pass-

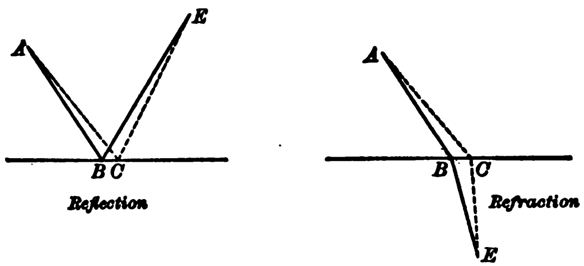


Fig. 36

age along ABE is less than that along any other route, such as ACE, and in the second problem you must bear in mind that the velocity in any medium is inversely proportional to the absolute refractive index of that medium. It would thus appear that rays of light always try to reach their destination as quickly as possible — a curious principle. It would be very interesting to trace its development, its limitations, and its applications to a variety of problems. However, there is no time for this now, nor can we do more than refer to the fact that this principle has suggested to science a much more far-reaching law, what is known as the Principle of Least Action, the greatest generalization of modern science. The principle was first enunciated a century and a half ago by Maupertuis, then president of the Berlin Academy.

He laid it down because, in his judgment, it was eminently in accord with the wisdom of the Creator. More modern men of science do not often feel so confident about sharing in the secrets of Providence; but they find the principle none the less useful in making for the great end they have in view — to comprehend all knowledge in a single law.

To return to the application of the laws of reflection and refraction, I repeat that it is necessary to limit myself very strictly. You will find large treatises on *Geometrical Optics*, which are taken up wholly with applications of the simplest of these laws, and whole books that treat of their bearing on the construction of special instruments. In the short time that remains in this lecture, it is obviously impossible to cover so much ground. I must select a single illustrative example, and deal with one optical instrument, and even with that in a very cursory manner. What is this instrument to be? The one most generally interesting would be the human eye, for there we have an optical instrument that we must all use. Apart from that, it is extremely interesting merely as an illustration of optical principles. It is truly a wonderful instrument or combination of instruments. It is at the same time a microscope, a telescope, a range-finder, a stereoscope, a photometer, a kinematograph, and an autochrome camera. An instrument that serves so many purposes can scarcely be expected to be free from imperfections, and the eye is not without its defects. At the same time, to the student of optics it is as interesting in its defects as in its strength. How to cure these defects or how to minimize their evil consequences is a human problem that requires for its successful solution an intimate knowledge of the scientific principles here discussed. However, the eye is not an instrument

that we have completely under our control; at the best we can supplement it. So it will be better for our present purpose to take another instrument, where there are no such limitations on our actions, and endeavor to indicate how our knowledge of the laws of light may be employed to make it as effective as possible. To this end, let us select the Astronomical Telescope, the purpose of which is simple and well known, — to enable us to see distant objects as clearly as possible, and in some cases to photograph their details or their relative positions.

I need not spend time in emphasizing the fundamental idea, which is to get an image of the object near at hand, and look at this image through a magnifier. You are all doubtless quite familiar with the idea of the image of an object. You can obtain this by reflection from a mirror which is either plane or curved. The plane mirror is the only perfect optical instrument, in the sense that it forms an image that is absolutely faithful to the original, free from all distortion or other defects. A curved reflector, as you know, produces a certain amount of distortion, which is very marked if the object be a large one, such as the human figure. You can also get an image by refraction, as with a pair of spectacles, a hand magnifier, or a photographic lens — with one or other of which every one is more or less familiar. However, although the fact of an image being formed in some such way is well known, you may not have thought of the mode in which this image is produced, or of the bearing of optical principles upon its formation. Here we have time only for the briefest outline. The fundamental principle, as usually stated, is that the image of a *point* is a *point*. Each point of an object has its image, and the whole collection of such points forms

a picture more or less like the original. Is it true, however, that the image of a point is a point? Yes, absolutely so, if the reflector be a plane mirror; but not so for any other case. In all such cases, if we take a series of points in the object, the rays from any one of them will, in general, after reflection or refraction, or both, at best pass *only approximately* through a corresponding point in the image. They may all pass very near indeed to this point in the image, but again, many of them may pass some distance away, and the clearness of the image will depend on *how close* to a point the rays from any point of the object converge. If we follow out the consequences of the laws of reflection and refraction, we find that the rays from a point converge more nearly to some other point if they all strike the reflecting or refracting surfaces *very nearly at right angles* than if they strike it at oblique and widely varying angles. The latter, at best, will give a blurred image; the former will make for clearness. Hence, in our telescope we must arrange that all the reflecting and refracting surfaces are "square on" to the impinging rays, and we must choose the form of these surfaces so that a slight departure from the perfect square will introduce as little indistinctness as possible.

In the case of a reflecting telescope the *form* of the reflecting surface is easily determined. The telescope being used for astronomical purposes, the incident rays come from extremely distant points, so that we have practically to deal with a series of parallel rays striking the reflector. It is a simple problem of geometry to prove under such circumstances that the form of reflector that will give the clearest image is a *paraboloid* — the surface formed by revolving a parabola about its axis. Figure 37 represents a

portion of a parabola of which AX is the axis, S the focus, AS the focal length, and BB' the aperture. The geometrical property of the parabola, which makes it useful for this optical purpose, is that if P be any point on the curve, and PR be drawn parallel to the axis, then the lines SP and PR make equal angles with PG, which is at right angles to the curve at P. Hence a ray of light that comes from a distant point in the direction PR will be reflected to the focus S, wherever be the point P.

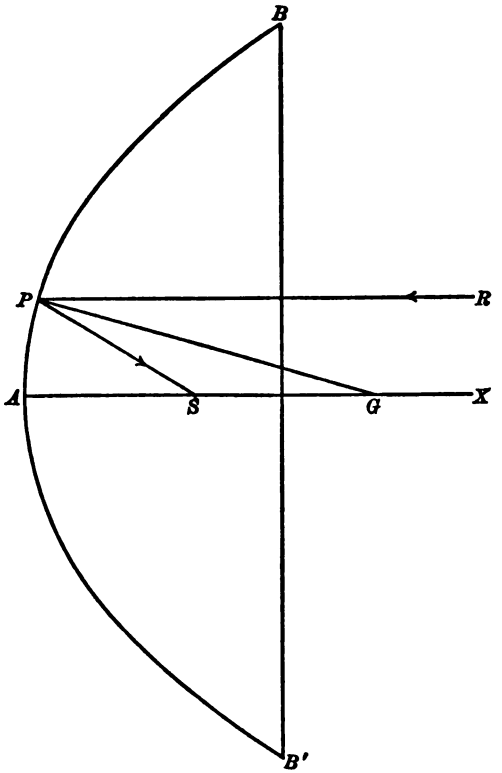


FIG. 37

So much for the form of the reflector; what next as to its material? We want to have the image as bright as possible, so we must have a surface with a high reflecting power. Theory and observation agree in indicating some of the metals as the

best reflectors. In the earlier reflectors speculum metal was commonly employed as being a fairly good reflector and not too expensive. Silver, however, is a much better reflector, and any objections to its use have been overcome by the discovery in recent times of thoroughly satisfactory methods of depositing it chemically upon glass. The thin film of silver is not expensive, and the glass supporting it, if carefully made, is fairly rigid, and so not very easily distorted. Freedom from distortion is extremely important where good results are required, for a slight change from the paraboloidal form will give different images in different parts of the reflector and a consequent blur. In fact, in the best modern reflectors, the greatest care is taken to preserve their form; they are kept as free as possible from changes of temperature, and the system of support is planned with the utmost thoroughness. It was mainly through lack of such precautions that the great reflectors of the past proved, in many ways, so disappointing.

Consider next the problem of the size of the reflector. What is to be its aperture BB', and its focal length AS? A considerable increase in aperture will make the instrument more cumbrous and greatly add to its cost. Its counteravailing advantages are mainly two. In the first place, a larger aperture collects more light, and so gives a brighter image. This may be a matter of great importance, if we wish to see or to photograph very faint objects. The brightness of the image depends upon the area of the aperture, and is therefore proportional to the square of the diameter BB'. Thus, if BB' be doubled, the brightness of the image will be increased fourfold. The second important advantage of a large aperture

will be more fully appreciated after we have dealt with Diffraction. In the lecture on that subject it will be shown that the image of a point is not a point, but a disk whose diameter depends upon the size of the aperture, being smaller for large ones than for small. If you are looking at two distant objects (*e.g.* a double star) through a telescope, each point will appear as a disk, and the smaller are the disks the less will they tend to overlap and produce a blurred effect. Hence, if great resolving power is required, the disks must be as small as possible, and this demands a large aperture. The first great reflector (that of Lord Rosse) was made more than half a century ago, and was 6 feet in diameter. After a time a reaction set in against reflectors, but they have come into prominence again of late, and now such an instrument, with the enormous aperture of 100 inches, is being made for the Mt. Wilson Solar Observatory. As to focal length, the advantage of increasing this is that the size of the image is magnified in proportion. If you double AS, you double the image, but there is a corresponding disadvantage in greater length of telescope, and so greater inconvenience and expense. Lord Rosse's telescope had a focal length of 54 feet and was exceedingly cumbrous.

Having considered such questions as the size, form, and material of the reflector, you may look for a moment at the problem of making the glass support for the reflecting film of silver. The glass must be as free as possible from flaws or strains, so as to minimize the danger of a change of shape, and to obtain a suitable disk of glass proves, in the case of a very large reflector, a very arduous process. Once this has been secured, the front surface of the disk is made concave by means of a tool of suitable curvature. It is important to avoid differences of curvature in different

parts of the surface, and any errors of this kind can be detected with extraordinary nicety — merely placing the finger on the glass will cause a swelling of the surface that can easily be detected. After a uniform curvature has been obtained, the next step is to set to work in the process of polishing to hollow out the surface in the center so as to produce an exact paraboloidal form, any departure from this form being readily discovered by a simple optical device.

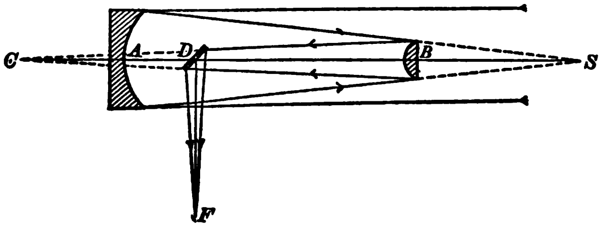


FIG. 38

Then the surface is silvered by one of those exceedingly ingenious devices of modern times designed for this end, and, let us hope, an almost perfect reflector is the result. Now, if such an instrument were turned toward a star or other heavenly body, it would produce an image of the object in the neighborhood of the focus S. With great focal length this image might be fifty feet or more away from A, and so would be inconveniently placed for purposes of close inspection. This inconvenience may be avoided by intercepting the rays as they converge toward S, and reflecting them backward so as to converge to a point C behind the large reflector (Fig. 38). It is a simple problem of geometry to determine, by the aid of the laws of reflection, the form of the reflecting surface that will produce this result. The surface must be a hy-

perboloid formed by the revolution about its transverse axis of a hyperbola whose foci are S and C, and it is made by the same general processes as are employed in forming the paraboloid. In order that the rays should reach C, a hole would have to be made in the center of the large reflector in the neighborhood of A. This has been done in some telescopes, but the plan has many disadvantages, and these may be avoided by again intercepting the rays as they converge toward C by a small plane mirror at D, and reflecting them to one side so as to form an image at F. A reflecting apparatus made in this way will give very good definition near the optic axis, but if the rays are oblique to this axis the images will be indistinct. It is therefore important that the instrument should be kept in almost perfect adjustment, and the greatest care must be employed to secure this, if the best results are to be obtained.

Thus far, in considering the formation of an image of an object, we have supposed that this is achieved by means of reflection. You need scarcely be reminded that the same end can be reached by means of refraction. You must all be more or less familiar with the action of a lens in bringing the rays of light from a point to a focus, and it is not difficult to investigate the features of the image thus formed, by aid of the laws of refraction. What has already been said as to the size of the aperture and the focal length of the lens applies to a refractor just as to a reflector. The *form* of the refracting surfaces is determined mainly from the consideration that two defects must be specially guarded against, these being known technically as *chromatic effects* and *spherical aberration*. The latter defect has already been referred to, without the name. It has been remarked that if rays from a point strike a surface obliquely,

they are not brought (either by reflection or refraction) to the same focus as when they strike the surface almost at right angles. If, then, we have a number of rays striking such a surface, some of them nearly normally and others much more obliquely, there will be no definite image of a point, and the whole image will be blurred and indistinct.

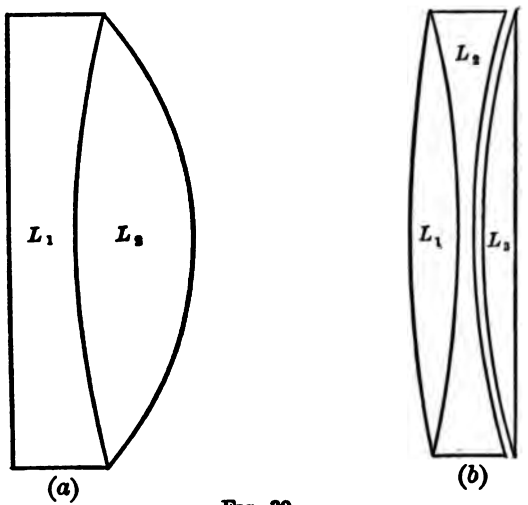


FIG. 39

Investigation shows that it is possible to lessen this indistinctness by increasing the number of refracting surfaces. A common arrangement is to have a *double objective*, such as is illustrated in Fig. 39 *a*. This is made of two lenses of glass of different refractive powers, one (L_1) of flint and the other (L_2) of crown glass. The curvatures of the various surfaces are arranged so as to make the defect due to rays striking one surface obliquely counterbalance that due to the other surfaces, and in every objective of any value this is done with great precision.

In constructing the lenses it is important to avoid having different curvatures in different belts of the lenses, as this will inevitably introduce aberration and cause a blur. Also, as the curvature of each surface must be maintained constant, care must be taken to avoid its change due to fluctuations of temperature, to flexure from the weight, or any other causes. The danger of flexure is of course much less serious with small lenses than with the large ones such as those of the great 40-inch refractor of the Yerkes Observatory. To avoid flexure with such large lenses, we must have considerable thickness in the center of the lens, and this introduces a serious defect when the telescope is to be used for photographic purposes. The amount of light absorbed in passing through a considerable thickness, even of the clearest glass, is far from negligible, and it increases enormously for those light-waves of high frequency which play the leading part in photographic work. Hence, if we wish to take a photograph of a faint object, so that we cannot afford to lose much light, a thick lens is objectionable. This is one of the reasons why refractors are being replaced by reflectors for some of the work in modern astronomy. Perhaps a stronger reason, however, is that the reflector avoids entirely the serious difficulties due to chromatic or color effects. The law of reflection is the same for all colors, so that the position of the image after any number of reflections is quite independent of the color of the light, and no chromatic effects can possibly be introduced by the process of reflection. With refraction, however, it is very different. The laws of refraction show that the position of the image depends on the refractive index of the refractor, and this again depends on the color of the incident light. White light, as we have seen, is a

composite of many colors, and the image formed by each of its constituents will be in a different place, and of a different size. Clearness and precision in the image thus appear to be impossible, and the question must arise — can this be avoided? The answer is that it can, at least in a partial manner. If we have two lenses, one may be made of such a form and material that it will throw the red image farther away than the blue, while the other reverses things by throwing the blue farther away than the red. In combination it may be arranged that they throw the two images together. This is one reason why the objective of an astronomical telescope is always made up of at least *two* lenses, such as the double objective depicted in Fig. 39 *a*. It is an easy matter to calculate how to arrange two lenses of given materials so as to combine any two given colors. If the telescope is to be used for visual work, it is natural to combine two colors to which the eye is most sensitive, such as green and yellow. This combination, however, will be of little use for photographic work, as the rays that are most important in that field have been neglected. To improve matters, we may do as Ritchey did with the Yerkes refractor, and put in a yellow screen to cut out the blue and violet; but of course we do this at the expense of the light that is most effective photographically, and it is often our great end to conserve what little light there is. In any case, when two differently colored images have been combined in this way, the other colored images are not, as a rule, combined. Their presence in different positions gives rise to what are called *secondary spectra*, which not only produce indistinctness, but cause a considerable loss in the light that contributes effectively to the brightness of the image. Thus it has been calculated that the loss from

this cause with the Lick 36-inch refractor was about one-quarter of the whole light, and with other refractors of shorter focal length the loss was considerably greater. Modern researches and experiments in the manufacture of glass have made it possible to select two glasses that in combination avoid these secondary spectra almost entirely. Unfortunately, however, the objectives so made have not been wholly free from defects, the most important arising from a lack of permanence in the quality of the glass. With a *triple objective* consisting of three lenses, L_1, L_2, L_3, such as is depicted in Fig. 39 *b*, the chromatic effects can be avoided almost perfectly, but as yet no very large refractors have been equipped in this fashion. The cost, of course, is greater, and the extra lens involves more loss of light by absorption, a serious thing, as we have seen, especially in the photography of faint objects.

So far we have been occupied entirely with the design and construction of the objective, which forms the image of an object, whether by reflection or refraction. We have still to inquire what means are employed to get a close view of the image so formed. For this purpose an *eye-piece* is used, and this is designed to magnify the image, just as when you take up a hand magnifier to look closely at a small object. Our time is too far exhausted to enable us to go into details as to the arrangement of the parts of this eye-piece. Suffice it to say that, as a rule, it consists of two lenses so constructed and placed as to diminish as much as possible the defects due to spherical aberration and the chromatic effects. It is not completely achromatic, but an effort is made to bring it about that the different colored images that are formed should have the same

apparent size, as this avoids the indistinctness due to a series of colored images overlapping one another.

The point that I have hoped to make clear to you in the latter part of this lecture is that the design and construction of a modern optical instrument is no haphazard process, guided by rule of thumb. On the contrary, every detail is carefully planned and calculated with the aid of the fundamental laws of reflection and refraction. Calculation, on the basis of these principles, determines the size and the form of the various parts; calculation determines their relative position, calculation determines even the materials of which they are made. Absolutely nothing is left to chance or guesswork; everywhere law and intelligence are supreme.

VII

THE PRINCIPLE OF INTERFERENCE

THUS far, in dealing with the theory of light, we have emphasized the idea of a *periodic* disturbance propagated through a medium, and we have emphasized this because the idea of periodicity is the fundamental one. Any such periodic disturbance may be called a *wave*, and the theory *a wave theory of light;* but it will be well to guard yourselves against being misled by following too closely the analogy presented by the familiar phenomena of water waves. Here, too, you have the fundamental idea of a periodic disturbance propagated with a definite velocity, and it is doubtless because of this that the phrase *a wave of light* is so generally employed. The analogy, however, is not complete, and must not be pressed too hard; for one reason, water waves, as ordinarily observed, are *surface phenomena;* if you could see what goes on below the surface, the analogy would be much more instructive. At the same time there is much that arises in discussing light that can be most conveniently spoken of in language that is suggested by the familiar phenomena of water waves. A common term when dealing with such matters is the *wave-length.* In the case of waves in water this is something that you can readily see and measure, the distance from crest to crest of consecutive waves. Suppose that you are watching a swarm of corks floating on the water, and observe how they rise and fall as waves pass over them. If

you fixed your attention on two successive corks, each of which was at the highest point of its path, they would, of course, be each on the crest of successive waves. After a definite interval of time (the period) they would each once more be on the crest of a wave, having fallen and risen in the interval as the wave-form advanced. The wave-length is the distance from crest to crest, and you can see that there must be a relation between the wave-length (λ), the velocity of the wave-form (v), and the period ($p = 1/f$, where f is the frequency). This relation is, in fact, $\lambda = vp = v/f$. In the case of light the velocity is always the same where there is no matter (that it changes with the frequency in the presence of matter was explained at considerable length in the lecture on Dispersion). Hence, as the frequency (f) changes with the color of the light, so must the wave-length (λ). In other words, differently colored waves have different lengths. Waves of high frequency, such as violet waves, are short; waves of lower frequency, such as red waves, are longer; what the actual lengths are and how they are measured will appear in a later lecture.

So far we have spoken of a single train of waves; but what if more than one train moves across the same space? It is an interesting and instructive thing to observe, if a sheet of water be at hand. Throw in two stones at *A* and *B* respectively. You will see a wave-form running outward from each of these centers, and in due time the two trains of waves will cross one another's path. A curious pattern will be the result, and you may learn much by trying to account for its leading features. The clue to everything here is the Principle of Superposition of Small Motions, or the Principle of Interference as it is usually called when its

applications to optical phenomena are under consideration. The principle lays down a rule for determining the effect of combining two *small* displacements due to different causes. It states that each cause produces the same effect as it would were the other cause absent, and that in computing the displacement due to the combination of both causes we have merely to add together the displacements due to each separately, of course taking account of the direction of the displacements in the process of addition. Thus, if the motion due to one cause would raise a point an inch, and that due to another would raise it half an inch, then the point would be raised $1 + \frac{1}{2}$, or an inch and a half, under the combined influence of both causes. If, on the other hand, one cause would raise a point an inch and the second depress it half an inch, the combination would raise it $1 - \frac{1}{2}$, or half an inch. Suppose that we accept this principle and apply it to two trains of water waves of the same height and length, and moving in the same direction. What would be the combined effect of two such waves? The answer would depend entirely on their relative *phase*. If crest corresponded to crest so that the waves were "in phase," the two would combine into a single wave of double the height of each. If, however, crest corresponded to furrow, so that there was a *difference of phase of half a wave-length, then the combination would produce no wave at all, but absolute rest.* The crest of one would just fill up the furrow of the other, and the two waves might be said to *interfere* with one another. It is on this account that the principle is commonly spoken of as Interference. It is a principle that was well known to Newton, and was applied by him to explain certain phenomena of the tides. However, it was

reserved for another great Englishman, Thomas Young, to realize that the same principle is applicable to light and to use it as a means of overcoming most of the obstacles that had retarded the progress of the science of optics. Young's is one of the very greatest names in science, although almost wholly unknown to the man in the street. He was endowed, according to Helmholtz, with "one of the most profound minds that the world has ever seen." His application of the Principle of Interference to light was only one of his strokes of genius; but it was far-reaching in its consequences, and made Young in a sense the father of the wave theory of light. It was he, more than any one else, who, in the early days, just a century ago, turned men's speculations along the track that has led to so much in more recent times. Perhaps you would like to hear how he expressed himself, as it is always interesting to listen to an original thinker when he is expounding his own ideas. Here, then, is a brief extract from his writings on the subject of Interference:—

"It was in May, 1801, that I discovered, by reflecting on the beautiful experiments of Newton, a law which appears to me to account for a greater variety of interesting phenomena than any other optical principle that has yet been made known. I shall endeavor to explain this law by a comparison. Suppose a number of equal waves of water to move upon the surface of a stagnant lake with a certain constant velocity, and to enter a narrow channel leading out of the lake. Suppose, then, another similar cause to have excited another equal series of waves, which arrive at the same channel with the same velocity and at the same time with the first. Neither series of waves will destroy the other, but their effects will be combined;

if they enter the channel in such a manner that the elevations of one series coincide with those of the other, they must together produce a series of greater joint elevations; but if the elevations of one series are so situated as to correspond to the depressions of the other, they must exactly fill up those depressions, and the surface of the water must remain smooth; at least I can discover no alternative, either from theory or from experiment. Now I maintain that similar effects take place whenever two portions of light are thus mixed, and this I call the general law of the Interference of Light. I have shown that this law agrees most accurately with the measures recorded in Newton's "Opticks," relative to the color of transparent substances, observed under circumstances which had never before been subject to calculation, and with a great diversity of other experiments never before explained."

I shall direct your attention in a moment to some experiments designed to test or illustrate the Principle of Interference, but before doing this I should perhaps state explicitly that in applying it to the explanation of optical phenomena you are not restricting yourself to any special form of the wave theory of light. It is a principle that is applicable to displacements of any kind, and its most important consequence for our present purposes is that an upward displacement in the ether due to one cause may be exactly counteracted by an equal and opposite downward movement due to some other cause, and that this will inevitably be the case if there be a certain phase relation between the two periodic movements. It is in this way that two lights may produce darkness in certain places, although it may at first seem paradoxical that a combination of lights should produce darkness. Further-

more, if you are to understand the experiments that are about to be referred to, you should call to mind that white light is of a composite character, and that, by suppressing some of its constituents, color effects are produced. At one place blue may be suppressed by interference, at another green, and at another red, so that interference phenomena should be characterized by bands of color wherever white light is employed in producing them.

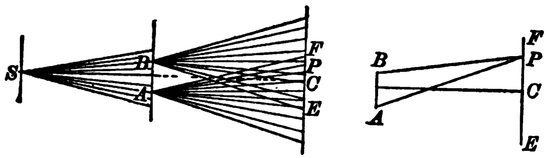


FIG. 40

One of the most famous of Young's experiments to test his theory of interference is, in principle, as follows. Light is allowed to stream through, say, a vertical slit the position of which is indicated by *S* (Fig. 40), and to fall on two other vertical slits, *A* and *B*, which are very close to one another in a screen parallel to that containing the first slit *S*. The light is intercepted on a vertical screen indicated by the section *ECPF* in the figure. Now if we consider a point such as *P* on this screen, it will be observed that it is illuminated by light that comes from two sources, *A* and *B* respectively. As things are arranged, the light that sets out from *A* at any moment will be in the same phase as that which has *B* as its starting-point; but that which travels to *P* along *AP* will reach *P* in a different phase than the light from *B*, for the two started together and moved at the same rate along roads of different lengths. If the point *P* be so

situated that the difference between AP and BP be half a wave-length, or any odd multiple thereof, the two lights reaching P will interfere and nullify one another. Hence the screen EF will not be uniformly illuminated, but there will be a series of dark vertical lines, or of colored bands, according as the incident light is homogeneous or otherwise. If one of the slits (A or B) be covered, the bands should disappear. All these phenomena may be observed, and the position of the bands and the arrangement of the colors are found to conform in the closest manner to the predictions of the theory thus sketched. Figure 41 gives an indication of the alternations of light and shade on the screen EF.

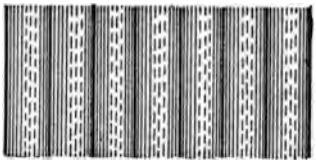


Fig. 41

Unfortunately, I am not able to show you Young's experiment, owing to the difficulty of exhibiting the phenomena to a large audience, but you will find it easy to make the experiment for yourselves. One method of proceeding is to rule two narrow lines very close to one another on a photographic plate that has been developed, and then to look through the slits so formed at the light that shines through a slit in front of a bright light, such as the electric light. A still simpler procedure is to make two pinholes close to one another in a card, and look through them at the light streaming through another hole. With a little care you will see the interference fringes quite distinctly. Another simple experiment designed to show interference is due to Fresnel, one of the great names in the development of the theory of light. He made light

from a slit S (Fig. 42) fall on two mirrors, A and B, that had their edges parallel to the slit and their planes inclined at a very small angle. After reflection from these two mirrors, the two streams of light were in a condition to interfere with one another, and a series of bands similar to those just described made their appearance on a screen PE. With this experiment, as with Young's, it is difficult to arrange things so as to exhibit the phenomena to many

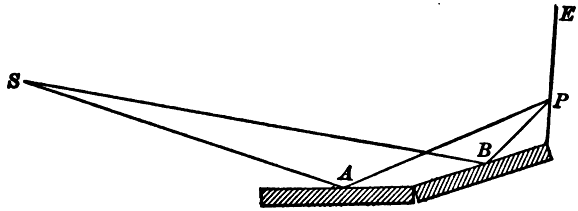


FIG. 42

persons at once, but you can repeat Fresnel's experiment for yourselves. Take two pieces of the same glass, blacken them on the back, and lay them on a board that is covered with a black cloth. Raise the edge of one strip of glass very slightly, and adjust the slit so as to be parallel to the common edge of the pieces of glass. With proper care in the adjustment, you will get interference fringes exhibited to the eye properly placed to receive the light, and you will find that these fringes disappear if one of the reflected beams is suppressed by blackening one of the mirrors. A modification of Fresnel's experiment, due to Lloyd, should perhaps be mentioned. Take a strip of plate-glass blackened at the back, and allow light to fall upon it at nearly grazing incidence, as in Fig. 43. Light from a slit S reaches a screen at P by two paths, one directly along SP, and the other along SBP after reflection at the mirror. These two

beams, the one direct and the other reflected, may interfere and give rise to fringes, as before. In this, as in all the experiments referred to recently, considerable care

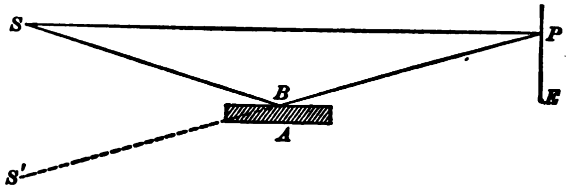


FIG. 43

must be exercised in the adjustments, otherwise no results or spurious results will be obtained. Fresnel's device, and Lloyd's modification of it, consist in producing interference between the two parts of a beam that have been separated by reflection. Fresnel also arranged to split the beam by means of refraction. To do this he employed a *biprism*, consisting of a piece of glass made in the form of two

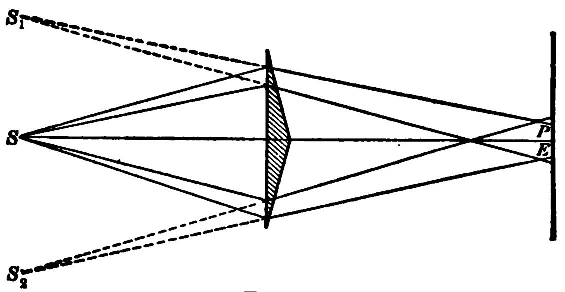


FIG. 44

prisms of very small angles placed back to back. In Fig. 44, the shaded portion represents a biprism, S a source of light, PE a screen. The light from S that falls upon the upper portion of the prism is bent downwards and made to pro-

ceed as if from S_1, while that which falls upon the lower portion is bent upwards and proceeds as if from S_2. Thus S_1 and S_2 correspond to A and B in Fig. 40, representing Young's experiment, and the explanation of the interference fringes is the same as was there indicated.

All these experiments are specially designed to exhibit interference fringes and to test the explanation by a comparison between theory and observation as to the exact position of the bands and the arrangement of their colors. Kindred phenomena, however, are obtained in almost countless other ways, many of them far more striking and beautiful than those to which reference has just been made. It has been explained that in order that waves of light may interfere, they must set out simultaneously from the same source and meet with such different treatment that one wave becomes half a wavelength in phase behind the other. Now think of a beam of light falling on a thin film of any material. Some of the light will be reflected at the first face, while some will penetrate the film, be reflected at the second face, and, after emerging from the film, be in a condition to interfere with what was first reflected. If the film be of the proper thickness, this interference will be inevitable, and as a consequence some of the light will be suppressed in places, so that we shall see alternations of light and darkness, or variations of color, according as the incident light is homogeneous or composite. You must all have observed the brilliant colors produced in this way by a thin film of oil on the surface of water. You may see the same thing here by looking at the beautiful color on the wall, produced by reflecting light from the surface of the water in this hand tray after a drop of turpentine has been allowed

to fall upon the water. Much more beautiful effects, due to similar causes, are obtained with a soap-film, as everybody knows who has seen a soap-bubble. Fortunately, youth is not a question of age, and the blowing of such bubbles has afforded interest and amusement to generations of young people between seven and seventy. Nor have philosophers been ashamed to enter into the game and to discuss the phenomena in their grave way. If it be true that to the poet's mind

> "the meanest flower that blows can give
> thoughts that do often lie too deep for tears,"

then it need cause no surprise that so common a thing as a soap-bubble has engaged the serious attention of the greatest men of science, such as Boyle and Newton of olden times, Stokes and Kelvin of our own day, to select only a typical few. All the gorgeous phenomena of color exhibited by soap-bubbles are explicable by means of the principle of interference. The color that is suppressed by interference varies with the thickness of the film, its refractive index, and the angle of incidence of the light that falls upon it. Theory enables us to calculate all the details and to predict what will happen with a film of given thickness when the wave-lengths corresponding to the different colors have been determined. How these wave-lengths may be measured will be indicated in a later lecture on Diffraction. Meanwhile, as the phenomena of the soap-bubble are somewhat complicated by the curvature of the surface, it may be well to show you similar color effects with a flat film. I dip this ring into a solution of soap, fix it in a vertical plane, and by means of a lens bring the light reflected from the film to a focus on

the screen. The exact interference effects depend on the thickness of the film, and therefore change as the thickness alters while the liquid streams down. The image on the screen is inverted by the lens, so that everything appears upside down. The upper part of the film is seen at the bottom of the picture on the screen, and you will observe that the liquid seems to be streaming *upwards*. Notice the changing color as the liquid thins away from the top of the film. First you see a bright green, then it changes gradually until now you have a deep red. Now, again, in this part it is blue, now violet, now quite black, and now the film has broken, having become too thin to bear the strain of its weight.

An interesting modification of this experiment is to arrange things so that the light comes from a narrow slit, and after reflection, as before, from the film, passes through a prism before falling on the screen. If light were reflected from a single surface and treated in this way, the prism would separate the different colors and produce the familiar spectrum. With the film, however, there will be places where the light is cut out by interference, so that, as the film thins, dark bands will be seen to travel across the spectrum. You can see them distinctly in the experiment that Mr. Farwell is now conducting.

You observed in these experiments with films that just before the film broke it looked quite *black* at the thinnest part. This is a curious fact, and one that seemed paradoxical for a time. Newton observed the same thing with an ordinary soap-bubble, and you can easily repeat the observation. Blow such a bubble, and cover it with a glass to screen it from air currents, and so prevent its breaking too soon. As the liquid drains downwards, the

film gets thinner at the top, and just before it breaks this part looks quite black. At first sight this seems contrary to what might be expected. As this portion of the film is extremely thin, it takes practically no time for light to travel across it and back to the upper surface, so that you might expect the light that has made this short passage to be in the same phase as the light that was reflected at the first surface. If this were so, the two waves should reinforce one another instead of interfering, so that we should have brightness instead of darkness. However, on examining the matter by the aid of theory, it appears that at one of the reflections, but not at the other, there should be a change of phase of half a wave-length in *the very act of reflection*, and this completely accounts for what is observed.

All the bands of color produced by interference that you have seen to-night have been arranged in straight lines, but it is easy to get them in other forms. Here, for example, is a simple modification of our experiment with the flat film. With these acoustical bellows I produce a slight blast and direct it almost tangentially on the surface of the film. This sets the liquid in the film in motion, and arranges it in regions of varying thickness, producing, as you see, brilliant curves of color. In one case you have a series of concentric circles, such an arrangement of color as is found in the famous phenomena of *Newton's Rings*. These Newton studied with great care, the second book of his "Opticks" being almost wholly devoted to a discussion of their features. Newton's arrangement for producing these rings is extremely ingenious, because extremely simple and extremely effective. It consists in pressing together two pieces of glass, one or

both of them being slightly curved (Fig. 45 *a*). When light is allowed to fall on this and to be reflected, a beautiful series of colored rings is seen arranged in concentric circles round a central spot. At all points such as *P* (Fig. 45 *b*) on a horizontal circle of which *O* is the center, the thickness of the air-space between the two pieces of glass is the same, and equal to *PN*. Thus waves that pass to and fro in this region have to traverse an air film of this thickness (*PN*). If, then, *PN* be of the length necessary to produce the requisite phase difference for

(*a*) (*b*)

FIG. 45

waves of a given length, there will be interference, and the corresponding color will be absent from this region. Thus, we should expect to see a series of colored rings if the incident light be composite like sunlight, and there is no great difficulty in predicting the main features from theory and verifying the correctness of this theory by careful observation of what actually takes place. The most important laws were discovered by Newton by induction from his experimental results. Thus, he found the law of the radii of the rings, viz. that at a given angle of incidence the radii of the different rings are proportional to the square roots of the numbers 1, 2, 3, 4... (These different rings are spoken of as rings of different *orders*.) He found also in what way the radii varied with the angle of incidence, and verified his law with wonderful accuracy, considering the rough instruments of measurement at his

disposal. The following table compares the radii of a ring of a given order for different angles of incidence on the glass, and shows how Newton's law and Newton's experiments agreed with one another. Moreover, by means of a prism Newton analyzed the light before it fell

Incidence	0°	10°	20°	30°
Radius (law)	1	1.0077	1.032	1.075
Radius (experiment) . .	1	1.0077	1.033	1.075
Incidence	**40°**	**50°**	**60°**	**70°**
Radius (law)	1.142	1.247	1.415	1.71
Radius (experiment) . .	1.140	1.250	1.4	1.69

upon his ring apparatus, and so was enabled to investigate the phenomena when employing light of a single color, and to see in what way a change of color affected the size of the rings and their distinctness. "I found," he says, "the circles which the red light made to be manifestly bigger than those which were made by blue and violet. And it was very pleasant to see them gradually swell or contract according as the color of the light was changed." As the radii of the rings depend on the color, the larger (red) rings of one order will tend to overlap the smaller (blue) rings of the next higher order. This overlapping will produce indistinctness, so that it will be difficult to see the rings of high order when the incident light is white. If, however, homogeneous light be employed, there is no possibility of overlapping, so that far more rings may be seen. "I have sometimes," says Newton, "seen more than twenty of them" (when working

with a prism to produce homogeneous light), "whereas, in the open air" (without the prism), "I could not discern above eight or nine." Instead of using a prism, we may get what is very nearly homogeneous light by interposing colored screens in front of the powerful electric light in the lantern. These screens cut off a good deal of the light, so that the phenomena, as you see, are not so brilliant as before; but if you look carefully, you will have no difficulty in making out the main features. Now there is a red screen and you see the red rings (of course no other color is possible with this arrangement); now we have a blue screen, and you notice the blue rings distinctly smaller than the red ones that you have just been looking at. Since Newton's day there have been many modifications of his experiments and many new phenomena of a kindred character discovered; but there is nothing that is not completely accounted for, down to the minutest detail, by means of the principle of interference coupled with the known laws of reflection and refraction.

All these examples of interference have been produced by apparatus that has been specially designed to exhibit this effect. Not infrequently, however, we meet with similar phenomena where no such pains has been taken to produce the result. In such cases the design, if design there be, is not of man's contrivance. Thus you have all observed that polished steel becomes colored when it is exposed to the air. A thin film of oxide is formed on the surface, and produces interference effects by reflection like any other film. Antique glass, especially when it has long been buried, becomes coated with a thin layer that shows beautiful interference colors. The wings of a butterfly owe their color to their delicate ribbed structure and the

interference that this produces. The gorgeousness of a peacock's tail is due to the same cause. You will observe that the color of this feather is not intrinsic; it changes with the incidence of the light, as you see when I turn it in the lime-light. The changing colors of opals are explained in the same way, and so are those of mother-of-pearl. If you examine such an object closely with a microscope, you will find that it is made up of layers, and that the surface cuts across these layers, and so presents a series of minute grooves. The lights that are reflected from opposite edges of these grooves are in the condition to interfere, and you can easily see that the color changes with the incidence of the light that falls upon the surface. None of this beautiful color is really *in* the shell. Brewster showed this conclusively when he stamped the shell on black wax, thereby reproduced the grooves, and obtained the same colors from the wax as from the original shell.

Before bringing this lecture to a close, there is just time to refer, all too briefly, to an ingenious application of the principles of interference to the problem of color photography. This was first made in 1891 by Lippmann, but since that date considerable improvements have been effected in the practical application of Lippmann's ideas. The theory of the process is not without its difficulties, but the broad lines of the explanation, as suggested by its author, are easily seen. The first matter that must be firmly grasped is that there is an intimate relation between the intensity of light reflected from a very thin film and its thickness. If the thickness be altered, so will the brightness of the reflected beam. We saw a short time ago that for a film so thin that it can scarcely be said to have any thickness, there is no light reflected at all. Start-

ing with this, let us imagine the thickness to increase gradually, and consider the effect on the intensity of the reflected light. For simplicity we shall suppose that the light is incident normally and not obliquely. The reflected light will grow in intensity until the thickness of the film is exactly half a wave-length of the light that is used. (That length will depend, as has been seen, upon the color of the light and upon the refractive index of the film.) After this thickness of half a wave-length has been reached, less light will be reflected, and this diminution will continue until a thickness of a wave-length has been attained, when once more there will be no reflected light. This variation of intensity is all accounted for by the principle of interference. We are thus led to the important conclusion that when dealing with thin films less than a wave-length in thickness, we immensely increase their reflecting power if we make their thickness half a wave-length of the light that we wish to reflect. Let us suppose that λ_R is the wave-length of red light for the material of which the film is composed, and that we make a film of thickness $\frac{1}{2}\lambda_R$, and observe the light that it reflects from a landscape or a picture. It will be much more effective in reflecting red than any other color, and its power of selective reflection will be greatly improved if we back it by several parallel films of the same thickness. With such an arrangement we shall practically see nothing but the red parts of the picture. With other films of thickness $\frac{1}{2}\lambda_G$, where λ_G is the wave-length for green light, we shall similarly pick out the green portions, and with films of thickness $\frac{1}{2}\lambda_V$ (where λ_V is the wave-length of violet light) the violet portions of our picture. If, now, we have any means of combining these

three colored reflections, we shall have a faithful representation of the original, according to the explanation set forth in the earlier lecture on color photography.

The practical difficulty in carrying out such a process that will probably first present itself to your minds will be that of obtaining films of the right thickness. The actual lengths of some waves of light will be set forth in the lecture on Diffraction, and if you have any conception of their minuteness, measured by any ordinary standard, you will realize that it is quite hopeless by any mechanical process to produce a film whose thickness is exactly $\frac{1}{2} \lambda_B$, or any of the other quantities that have been specified. And yet such films can be manufactured quite accurately by optical means. The device for doing this is, of course, an essential feature of the Lippmann process; but the same principle was employed a little earlier by Wiener. It is another simple application of the Principle of Interference. Suppose that we have two series of waves moving through a medium, and that they are similar in every other respect *except that they are moving in opposite directions*. These waves will be in a condition to interfere with one another, and there will be a series of points N_1, N_2, N_3... at each of which the upward displacement in one wave is exactly counteracted by the downward displacement in the other wave that is moving in the opposite direction. At such points, which are called *nodes*, the displacement due to the two waves will be zero. At intermediate points, L_1, L_2, L_3..., the two displacements will be in the same direction, and will reinforce one another, and these points, where there is a maximum of displacement, are called *loops*. Investigation shows that the positions of these nodes and loops are stationary, that they do not

change from moment to moment. The aspect of this combination of two trains of waves is thus very different from that of either taken separately. The nodes always remain at rest, and halfway between these points (at the loops) the crests of the waves rise and fall periodically. There is no moving of the wave-form in one direction or the other, but a mere gradual change of height. Such a set of waves are consequently called *stationary waves.* They have often been set up in air and water; but the difficulties of producing them with light-waves in the ether and of demonstrating their existence were not successfully overcome till 1890. In that year Wiener set up these stationary waves by reflecting light from the silver coating of a plate of glass, and proved their existence by their effect on a thin film of sensitized collodion superposed on the glass. We should expect the photographic action to be different at the nodes, where there is no displacement, than at the loops where the displacement is greatest, and Wiener succeeded in showing that the photograph was crossed by bright and dark bands at regular intervals, and thus in affording another ocular demonstration of the soundness of the Principle of Interference. Now there is one feature of these stationary waves that has not yet been mentioned and that is specially important for the purpose that we have in hand. *The distance between successive loops, as well as that between successive nodes, is exactly half a wave-length.* You will realize the significance of this at once. It gives us an optical means of producing a film, or a series of parallel films, whose thickness is half a wave-length of any color that we wish to use. Set up these stationary waves with red light, and they will so act on the sensitive emulsion as to arrange it

effectively in layers whose thickness is $\frac{1}{2}$ λ_R, and when this is afterwards viewed by reflection it will send back practically nothing but red light. Do the same with the other colors, and this part of your problem is solved. You will probably see, too, that it is not really necessary to have these different films and to devise a means of combining the pictures that they present by reflection. All the work can be done by the same material. Each color that strikes it will build up a little film by means of stationary waves acting on the sensitive emulsion with special force at regular intervals of half a wave-length, and this film will be of just the right thickness to reflect that particular color most copiously. The *form* of the object will be produced, just as in ordinary photography, by the gradations of light and shade over different portions of the plate; the *color* by the thickness of the different films beneath the several portions.

VIII

CRYSTALS

TO-NIGHT we are to deal with some of the optical properties of crystals. It has been remarked in an earlier lecture that the distinguishing feature of a crystal is its structure. Its parts are not thrown together at random, but are built one upon another according to some definite plan. The result is that a crystal does not seem the same when looked at from different directions. If you could imagine yourself moving through water or glass (which are not crystals), it would make no difference to your rate of progress whether you went north, south, east, or west. In a crystal, however, it might well be different; the structure might be so arranged as to make progress easier in one direction than in another. In optical problems we are interested especially in the propagation of waves, the speed of which for a medium like the ether depends on the rigidity of that medium. Here we need not stop to inquire exactly how the presence of matter modifies the effective rigidity of the ether containing it; but owing to the structure of a crystal it is natural to suppose that its presence in the ether will modify the rigidity differently in different directions. If we apply general dynamical principles to the discussion of the propagation of waves in such a medium (that is, a medium with different rigidities in different directions), the first

striking result that we reach is that, as a general rule, for a wave traveling in any given direction there are *two* speeds with which the wave can travel. We may express this by saying that two waves can travel through a crystal in any given direction, and that in general these will travel with different speeds. As there is a ray of light corresponding to each wave, we see that when a ray strikes a crystal it will give rise not to one, but to *two* different rays within the crystal. This prediction from theory cor-

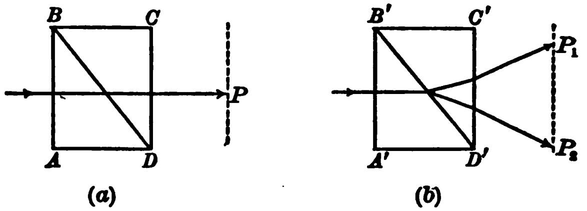


Fig. 46

responds to the well-known fact of *double refraction* produced by a crystal. Here are two double prisms of the same size and shape. They are represented in section in Fig. 46 *a* and *b*. The first is made of two prisms, *ABD* and *BDC*, of the same non-crystalline material, glass. The second (Fig. 46 *b*) is made in exactly the same way, but is of crystal, Iceland spar. Now observe the difference of behavior when a ray of light falls perpendicularly on a face of each double prism and is afterwards received on a screen behind the prism. With the glass the ray goes straight through as indicated in Fig. 46 *a* and forms a single patch at *P* on the screen. With the crystal the ray splits into two on crossing *B'D'*, each of these rays is further bent on passing out of the prism, and on the screen we see two widely separated spots of light, one at P_1 and

the other at P_2. You see, then, that this double refraction is no dream of the theorists, but an actual fact.

Theory, however, does much more than predict that we should find two waves traveling in a given direction with different speeds. It indicates, further, and this is very important, that these two waves will be *differently polarized.* When each is plane polarized, the planes of polarization for the two waves are at right angles to one another. This deduction from theory is amply verified by experiment, and the use of crystals to produce or to test plane polarized light is one of the regular resources of an optical laboratory. You may remember that in introducing the subject of Polarization we employed a Nicol's prism to produce plane polarized light. Its power of doing this depends entirely on its crystalline structure, and you should have no difficulty in understanding its action if you bear in mind two facts. The first is the one just referred to, that for a given ray in a crystal the vibrations must be confined to one or other of two planes at right angles, say a vertical and a horizontal plane. It appears that the molecules of a crystal are so arranged that the ether cannot continue to vibrate to and fro along any arbitrary direction, but must confine its movements to one or other of two directions at right angles to one another. A mechanical analogue was suggested on p. 101 and illustrated in Fig. 24; but it may not be out of place to repeat that this is merely an analogy, and that it is not suggested that the figure depicts the actual arrangement of the molecules. The second fact to remember in dealing with Nicol's prism is the fact of total reflection when the angle of incidence exceeds the critical angle. Nicol's prism is made by cementing together two prisms

of Iceland spar, as indicated in Fig. 47. When a ray *AB* strikes the prism, it is split into two by double refraction, and the two rays in the crystal *BC* and *BF* are differently polarized, *BC* horizontally (say) and *BF* vertically. The angles of the prisms are so arranged that *BF* strikes the thin layer of cement between the prisms at an angle greater than the critical angle. Thus, the ray *BF* is *totally* reflected along *FH*, and so does not emerge from the face *D*.

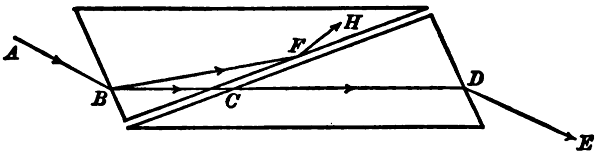


Fig. 47

The other ray, *BC*, passes over into the second prism and emerges at *D*, *polarized in a horizontal plane.*

It has been stated above that, *in general*, two different waves may be propagated in any direction. Theory, however, indicates, and experiment verifies, that there must always be *one*, and in some cases *two*, directions in which only a single wave can pass. Those directions are called the *optic axes* of the crystal, and crystals are classified into *uniaxal* and *biaxal*, according as they have one or two of such axes. In the first case the arrangement of the molecules of the crystal must be perfectly symmetrical round the axis; in the second case there is no such perfect symmetry about any line. Theory, moreover, does much more than indicate these general features; it enables us to calculate all the details of the wave-motion. Thus we can compute exactly the speeds with which waves will travel in any given direction. It is convenient to express the

speed in terms of the refractive index, it having been explained before that the speed is obtained by dividing a known constant by the refractive index. The results can be exhibited in a geometrical form by drawing lines from a point O, the directions of the lines indicating the direction in which the wave is traveling and the length of the line measuring its refractive index. If lines are drawn in all directions in this way, their ends will all lie on a surface, which is called the *Index Surface.* Theory predicts the precise form of this. In the case of uniaxal

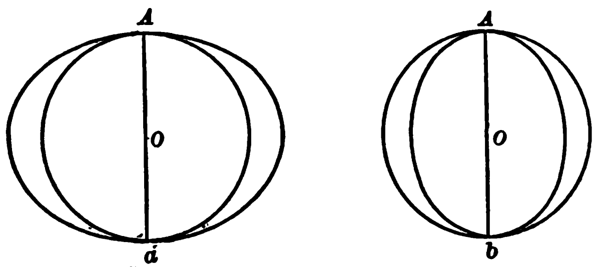


FIG. 48

crystals, where there is perfect symmetry about an axis, the index surface consists of a sphere and a spheroid, with the optic axis as a common diameter. A spheroid is an egg-shaped surface with perfect symmetry about an axis, so that you may think of the index surface for a uniaxal crystal as being made up of an egg and a sphere. You will realize at once that the surface might have two distinct forms: the sphere might be inside the egg (Fig. 48 *a*), or the egg might be inside the sphere (Fig. 48 *b*). The crystals will have different optical properties in the two cases, and those of the first type are called *positive crystals,* those of the second *negative crystals.* You will see from

the figure that a line drawn in any other direction than the optic axis OA will cut the index surface at two different distances from the center O, when it crosses the sphere and the spheroid respectively. These two distances represent the refractive indices (and so measure the speeds) of the two waves that, we have seen, can be propagated in any direction. You will notice that the law which connects the refractive index with the direction of propagation is quite different for the two waves. With the sphere the radius is everywhere the same, so that for the corresponding wave the refractive index is the same in all directions. This is the case with ordinary non-crystalline substances, so that the ray obeys the ordinary laws of refraction already discussed, and is consequently called the *ordinary ray*. This deduction from theory, according to which one of the rays in a uniaxal crystal should obey the ordinary laws of refraction, has been completely verified by experiment. Very careful estimates of the refractive indices have been made for waves in all directions, and it is found that the refractive index is absolutely constant, or more strictly, the variations in its measurement never exceeded 0.00002, a variation well within the limits of the probable errors of the experiments that were made.

So much for one of the waves within a uniaxal crystal. With the other wave and its corresponding ray the law of refraction is less simple, and as the ordinary law is not obeyed, the ray is called the *extraordinary ray*. As you see from Fig. 48, the length of the line drawn from the centre O to the surface of the spheroid varies with the direction of the line, so that the refractive index varies with the direction of propagation of the wave. It is a simple problem of geometry to compute its value for any

direction, making a known angle θ with the optic axis. The following table shows a comparison between theory and observation for the refractive index (n) corresponding to different directions (θ). It will be seen that the agreement is excellent, the differences being of the order of the probable errors of experiment: —

θ	n (THEORY)	n (EXPERIMENT)	θ	n (THEORY)	n (EXPERIMENT)
0° 2′ 40″	1.66779	1.66780	46° 46′ 2″	1.56645	1.56653
4° 19′ 58″	1.66660	1.66663	49° 23′ 10″	1.55861	1.55876
7° 51′ 58″	1.66387	1.66385	52° 42′ 6″	1.54902	1.54914
11° 23′ 12″	1.65967	1.65978	58° 39′ 10″	1.53303	1.53312
17° 8′ 26″	1.64987	1.64996	61° 39′ 33″	1.52570	1.52573
20° 26′ 1″	1.64279	1.64287	63° 9′ 6″	1.52228	1.52241
23° 50′ 45″	1.63451	1.63455	66° 14′ 27″	1.51579	1.51571
25° 49′ 35″	1.62934	1.62930	72° 18′ 55″	1.50476	1.50475
29° 18′ 42″	1.61965	1.61974	75° 36′ 18″	1.50009	1.50005
34° 48′ 0″	1.60336	1.60336	79° 6′ 26″	1.49612	1.49610
35° 58′ 47″	1.59048	1.59058	80° 14′ 4″	1.49507	1.49507
40° 49′ 21″	1.58478	1.58487	87° 6′ 40″	1.49112	1.49114
45° 45′ 57″	1.57000	1.57014	89° 49′ 6″	1.49074	1.49074

These results have reference to uniaxal crystals which are perfectly symmetrical about a line. With biaxal crystals there is no such symmetry, and the optical properties are consequently more difficult to deal with. However, the same general principles lead to a complete solution of the problem, although the results are much less simple. The index surface no longer consists of a sphere and a spheroid, but of two sheets that are less familiar in form. Its geometrical properties can be investigated mathematically and the values of the refractive indices for waves in any given direction easily computed. The

following table, corresponding to that just given for a uniaxal crystal, compares theory and experiment for a number of different directions in a biaxal crystal. In this table n_1 is the refractive index corresponding to the inner sheet of the index surface, while n_2 represents the same quantity for the outer sheet:—

θ	n_1 (THEORY)	n_1 (EXPERIMENT)	θ	n_2 (THEORY)	n_2 (EXPERIMENT)
0	1.68103	1.68099	0	1.68533	1.68526
3° 12′ 50″	1.67714	1.67721	7° 9′ 10″	1.68465	1.68454
13° 6′ 20″	1.66298	1.66300	17° 2′ 40″	1.68445	1.68448
21° 4′ 30″	1.64607	1.64603	25° 0′ 50″	1.68443	1.68452
28° 14′ 10″	1.62824	1.62807	32° 10′ 30″	1.68443	1.68447
35° 29′ 20″	1.60900	1.60897	38° 27′ 30″	1.68444	1.68453
45° 14′ 50″	1.58363	1.58365	49° 13′ 0″	1.68445	1.68457
60° 1′ 30″	1.55154	1.55157	63° 59′ 30″	1.68447	1.68452
69° 37′ 40″	1.53784	1.53774	73° 35′ 50″	1.68448	1.68444

When we wish to estimate the velocities of the waves that can travel through a crystal in any direction, it is convenient, as has been seen, to know something of the form of the Index Surface for the crystal in question. There is, however, another surface which is referred to perhaps even more frequently in discussions of the optical properties of crystals. This surface is known as the *Wave Surface*, and we must try to realize what is its significance. If you throw a stone into a pool and watch the waves spreading outward, you will have no difficulty in observing the position of the crest of the moving wave at the end of any time, such as a second. As the wave moves out with the same speed in all directions, the crest will form a circle round the original point of disturbance as

center. If, instead of dealing with surface waves, you had waves that spread out in all directions with equal velocities, then it is clear that after a second the crests would all lie on a sphere. This, then, is the *wave surface* for a uniform medium, the surface that contains the crests of all the waves that have been moving outwards for a given time, such as a second. In a crystal the waves move with different speeds in different directions, so that the wave surface is no longer spherical. Its form can be determined from theory, and its geometrical properties discussed as fully as may be desired. As there are two waves in any given direction, the wave surface consists of two sheets, as does the index surface, and, just as with that surface, its form is specially simple for a uniaxal crystal. In that case the wave surface is made up, like the index surface, of a sphere and a spheroid, as shown in Fig. 48, with the difference, however, that (*a*) is the wave surface for a negative, and (*b*) for a positive crystal.

A knowledge of the form of the wave surface is very helpful when dealing with the optical behavior of a crystal. It enables you, for example, to determine the directions of the rays corresponding to waves in a given direction and to exhibit by a simple geometrical construction the directions of polarization in the two waves. The theory shows that a ray is represented by the line drawn from the center of the wave surface to the point of contact with this surface of a plane which touches it, and is parallel to the front of the advancing wave. I hold in my hand an apple, and will suppose for the sake of illustration that it represents a wave surface. In my other hand I have a sheet of paper, and I shall take this to represent the front of a wave of light moving through the crystal. The direc-

tion of this wave-front being known, the problem before me is to determine the direction of the corresponding *ray* of light. Move the sheet of paper parallel to itself until it touches the apple at P; then, according to the theory, if O be the center of the apple, corresponding to the center of the wave surface, OP is the direction of the ray. In reality, of course, the wave surface differs very obviously from the surface of an apple. It has symmetry about a point O, its center, and it consists of *two sheets*, so that planes in a given direction (both perpendicular to a given line ON) will touch it at two points, P_1 and P_2 (one on each sheet), on the same side of the center O (Fig. 49).

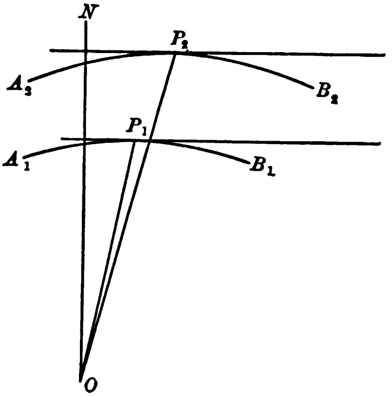


FIG. 49

In this figure the curves $A_1P_1B_1$ and $A_2P_2B_2$ represent portions of plane sections of the two "sheets," as they are called, of the wave surface. OP_1 and OP_2 represent the two rays for waves propagated in the direction ON, and it should be understood that the three lines ON, OP_1, and OP_2 are *not*, in general, in the same plane.

If you will return for a moment to the case of this apple, you will see that as I move the sheet of paper in different directions it touches the apple, *as a rule*, just in one point. However, there is one striking exception to this general rule. Now I hold the paper at right angles to the stem of the apple, and you observe that it touches the apple

not in a single point, but in an infinite number of points encircling the stem. The apple, as has already been remarked, is very different in form from the wave surface, but the two surfaces have some points of similarity. If you were to make a model of the wave surface, you would find that it has four points that closely resemble that on an apple near the stem (*singular points* is their technical name), and that a plane that touches the surface in the neighborhood of one of these points touches it not at an isolated point, as is the general rule, but at an infinite number of points forming a circle round the singular point. It should still be true that a line drawn from the center of the wave surface to any one of these points where the plane touches the surface should represent a ray of light corresponding to a wave-front parallel to the plane in question. All the lines drawn thus from the center to the various points of contact will form a *cone*, so that we should expect that if we could get a wave of light to travel in the right direction in a crystal, we should see not two rays only, as in the ordinary case of double refraction, but a whole cone of rays. That this phenomenon was to be expected was first suggested from theoretical considerations such as have just been indicated. The theory was developed by Sir W. Hamilton, and, at his instigation, was put to the test of experiment by Lloyd. Knowing what to look for, Lloyd had not much difficulty in observing this phenomenon, and it is now well known under the name of *Conical Refraction*. With the crystal used by Lloyd, Hamilton's theory indicated that the angle of the cone of rays formed in this way should be 1° 55′, and Lloyd's measurements made it 1° 50′, the agreement being as close as could be expected in the determina-

tion of such a quantity. Here, then, we have an example of something whose existence had never been suspected until the theory of light suggested the search for it. Much has been made of this prediction from theory, perhaps too much. We have already seen far more wonderful agreement between theory and observation in other fields of optics, the only peculiarity of this case being that the theory came before the observation and not *vice versa*. However, it should be remembered that the one aim of the theory is to fit the facts, and it makes little difference to the value of the theory whether the facts happen to have been previously observed or not. This may be largely a matter of accident, and the only advantage that can be claimed for a theory that predicts the unknown is that its power to do so should inspire extra confidence, seeing that the theory cannot have been suggested by this fact that is being explained, as is often the case with "explanations."

In a previous lecture we saw how successfully the theory of light can deal with the problem of reflection and refraction at the surface of a non-crystalline medium such as glass or water. It is equally successful in its treatment of crystals. Once the general laws of wave propagation in such media are understood, there is no special difficulty in proceeding by means of dynamical principles to calculate the amplitudes and phases, as well as the directions and velocities, of the various waves that may arise. Of course, the mathematical processes are more complex than when we are dealing with non-crystalline substances, but all the difficulties that present themselves have been overcome. Just a few of the results may be referred to here, in so far as they can be tested by experiment.

We have seen that, with a non-crystalline substance, if light be incident at a certain angle, an angle that goes by the name of the polarizing angle, the reflected light has the peculiarity of being *plane polarized.* The position of this angle for any substance is easily determined from the simple law, due to Brewster, that the tangent of the angle is equal to the refractive index of the substance. In the case of crystals, theory indicates that there will also be a polarizing angle, but that the law from which it may be computed is less simple. With crystals the refractive index is not a constant, but depends on the direction in which the wave is being propagated and the nature of its polarization. We should expect, therefore, that the polarizing angle would depend on these things, and in this theory and observation agree. The following table gives a comparison between theory and observation as to the values of the polarizing angle under different circumstances of reflection from a uniaxal crystal. The angle is different according as the plane of incidence is parallel or perpendicular to the plane containing the optic axis of the crystal. These two cases are distinguished by subscripts; thus, P_1 and P_2. The angle θ is the angle that the optic axis makes with the reflecting face of the crystal. The results are shown graphically in Fig. 50: —

θ	0° 25′	27° 2′	45° 29′	64° 1′ 30″	89° 47′
P_1 (theory) . . .	54° 3′	55° 25′	57° 25′	59° 25′	60° 41′
P_1 (experiment) .	54° 12′	55° 26′	57° 22′	59° 19′	60° 33′
P_2 (theory) . . .	58° 55′	59° 17′	59° 48′	60° 23′	60° 41′
P_2 (experiment) .	58° 56′	59° 4′	59° 48′	60° 75′	60° 33′

In the case of reflection from a non-crystalline substance we have seen that at the polarizing angle the reflected light is polarized in a plane parallel to the plane of inci-

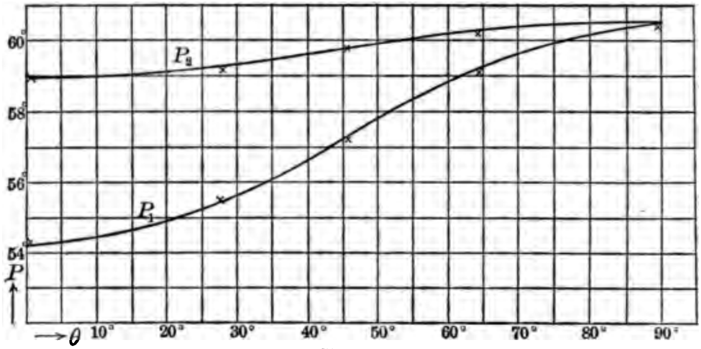


Fig. 50

dence. With a crystal, however, this is not the case. The plane of polarization deviates from that of incidence, being inclined to it at a small angle, Δ, which can be calculated from theory. The values of Δ obtained from theory and experiment were as follows, for the case of reflection from a uniaxal crystal whose optic axis was parallel to the reflecting surface. The angle *a* denotes the angle between the optic axis and the plane of incidence.

a	0°	22° 30′	45°	67° 30′	90°
Δ (theory)	0	2° 46′	3° 54′	2° 46′	0
Δ (experiment) . .	0	2° 46′	3° 57′	2° 43′	0

When dealing with ordinary reflection, we made a comparison between theory and observation as to the difference of phase between two reflected waves which are

polarized respectively parallel and perpendicular to the plane of incidence. The corresponding problem for crystalline reflection is more complex, but the general character of the results is the same. This will be seen at once by comparing Fig. 51, which shows how the difference of

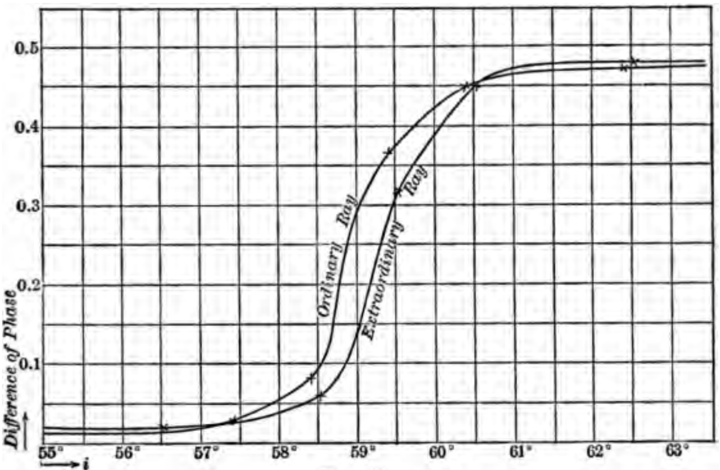


FIG. 51

phase depends upon the angle of incidence in reflection from a crystal, with Fig. 32 of the earlier lecture.

In this, as in some other lectures, I have brought before your notice a number of tables and figures that will probably prove attractive or repellent according to the degree in which you realize their significance. Their object in all cases is to show how well, or how ill, the theory fits the facts, and I hope that by this time their cumulative effect will have convinced you that the modern theory of light keeps always very close to the solid ground of fact. Such things are full of interest to a serious scientist, as they

give him what, above all, he is anxious to have, a searching test of his theories; but the optical effects with which they deal do not make a very wide appeal. They would not usually be described as beautiful, and few men, outside the narrow circle of the physicists, would display much enthusiasm over tables of refractive indices, polarizing angles, and the like. It happens, however, that with crystals we can produce effects that are generally recognized as extremely beautiful, and that the careful observation of some of these also serves, in a measure, as a test of the accuracy of our theory of the propagation of light in a crystal. You are aware, perhaps, that if you make a solution of tartaric acid, pour it over glass, and evaporate the water by means of a steady heat, you may, with proper precautions, get a film of minute crystals of the acid deposited on the glass. Here is a glass disk upon which is such a deposit. I place it between these two Nicol's prisms, and allow the bright light from the lantern to shine through the apparatus. If you direct your attention to the screen, you will admit, at any rate, that the colors are very gorgeous, and probably that the picture is a beautiful one. Its beauty is enhanced by its irregularity, and this is due to the fact that the little crystals on the glass present their facets to the light at angles of all sorts. There is thus a total absence of that mathematical precision which is the only objection that can be brought against the claim of beauty made on behalf of the phenomena with which we are to be occupied during the remainder of this lecture.

These phenomena are all produced by interposing a thin crystalline plate between two Nicols. The effect of each Nicol is to confine the vibrations to a definite plane,

so that the light that gets through a Nicol must be plane polarized in a direction that depends on the way in which the Nicol is turned. The effect of the plate of crystal is to split up the incident wave of light into two waves, moving forward with different speeds. By the time that these two waves have traversed the crystal, they will have

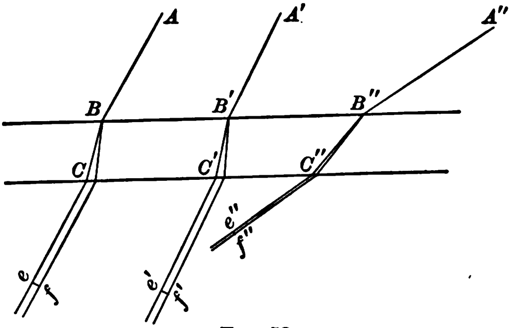


FIG. 52

got out of phase, and if their difference of phase be of the right amount, then, as we saw in the last lecture, they will interfere and in combination produce darkness. If we arrange things so that at different points of the plate the difference of phase between the emerging waves is different, then there will be interference at some points and not at others, so that we shall get alternations of light and darkness. It is easy to see that if the incident beam be parallel, we shall have no such alternations, but uniform brightness (or darkness) over the plate. If *AB* (Fig. 52) represent the front of a wave falling on the plate, this will set up two waves moving with different velocities, and these will emerge from the plate with a difference of phase represented by *ef* in the figure. If *A′B′* and *A″B″*

be other wave-fronts, the phase differences on emergence will be $e'f'$ and $e''f''$ respectively. Now it is obvious that if $A'B'$ be parallel to AB, as will be the case if the incident beam be parallel, then $e'f'$ will be equal to ef. Thus the phase difference in the neighborhood of C' will be the same as that at C, and it will be equally bright at these two

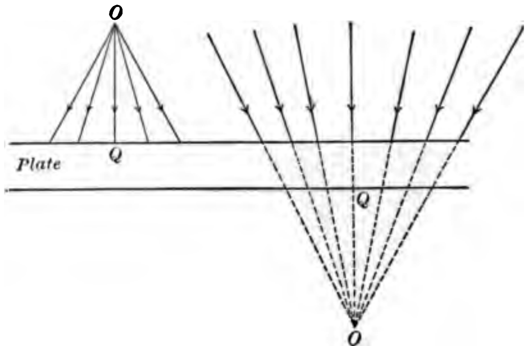
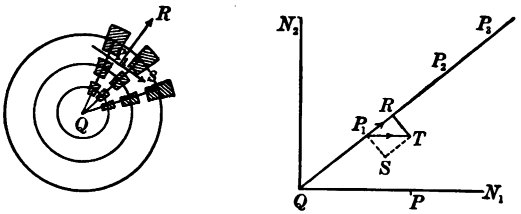


FIG. 53

points. If, then, we want alternations of light and darkness, we must abandon a parallel incident beam. If we arranged that the incident beam should diverge from or converge to a point, as indicated in Fig. 53, then any two wave-fronts would not be parallel, but would be inclined to one another, as represented by AB and $A''B''$ in Fig. 52. The differences of phase on emergence would be ef and $e''f''$, and as these are different it might be bright at C and dark at C''.

We shall suppose that things are arranged to avoid a parallel beam, and that the incident pencil of light is of a diverging or converging character, with OQ for its axis. We shall then examine the simplest case that can be presented, that of perfect symmetry, where we have a uni-

axal crystal, the plate of which is cut at right angles to the optic axis, the direction of this axis coinciding with that of the incident pencil. If we were to look down upon the plate in the direction of the axis, and observe a plan of the mechanical analogue referred to on pp. 101 and 177, then, as there must be perfect symmetry about the axis, the arrangement of the obstacles would be that represented in Fig. 54 *a*. At any point, P_1, the vibrations



(*a*) (*b*)

FIG. 54

must be confined to one or other of two directions, P_1R and P_1S, at right angles to one another. Of these the first, P_1R, is along the direction QP_1, and the second is at right angles to this. Now suppose that the first Nicol is so placed that it stops all vibrations except those parallel to QN_1 (Fig. 54 *b*). Then P_1T, which is parallel to QN_1, may represent a displacement in the incident wave as it strikes the crystal plate. Before considering what happens to the wave within the crystal, it is convenient to "resolve" the displacement P_1T into its equivalent, P_1R combined with P_1S, or what is the same thing, P_1R combined with RT. It will be seen that RT is equal and parallel to P_1S, so that these two lines represent displacements of the same magnitude and in the same direction. [This

"resolution" of a displacement P_1T into two displacements, P_1R and RT, according to the "triangle law," is really a very simple matter, it being obvious that the final displacement is the same, whether you go direct from P_1 to T, or by two stages from P_1 to R, and then from R to T.] Instead, then, of saying that in the incident wave there is a displacement P_1T parallel to QN_1, we may say that there are two displacements, one, P_1R, being in the direction QP_1, and the other, RT, at right angles to this. Displacements in the first of these directions are characteristic of one of the waves that the crystal can transmit, while displacements in the other characterize the second wave. These two waves, as we have seen, traverse the crystal with different speeds, and emerge with a difference of phase. What this phase difference is will depend, as appears from Fig. 52, on the angle at which the incident wave strikes the face of the crystal. This will be the same for all points P_1 that are at the same distance from the axis Q, but will be different at different points along the line QP. Let us suppose that the point P_1 is so placed that the phase difference is one wave-length for the color under consideration. How will the two waves of light of this color combine after they pass through the second Nicol? That, of course, will depend upon the position of this Nicol. Let us suppose that the two Nicols are "crossed," so that the second Nicol stops all vibrations except those in the direction QN_2 (Fig. 54 *b*), where N_1QN_2 is a right angle. Draw RU (Fig. 55) parallel to QN_2 and therefore perpendicular to P_1T or QN_1. The displacement represented by P_1R is equivalent to a combination of two displacements, represented in magnitude and direction by P_1U and UR respectively. The displacement P_1U is,

however, annulled by the second Nicol, which will not permit a wave to pass unless the displacements therein are parallel to QN_2. We see then that, while P_1R represents the displacement in one of the waves that emerges from the plate of crystal, after this wave has traversed the second Nicol the displacement is changed to UR. The displacement in the other wave, represented by RT, may be dealt with similarly. It is equivalent to two displacements, RU and UT, and of these the second is annulled by the Nicol, so that the displacement in this wave as it comes through the Nicol is RU.

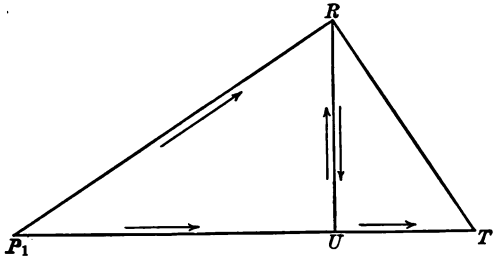


FIG. 55

Now we have supposed that P_1 is so situated that the difference of phase between the two waves is exactly a wave-length, and this, as far as optical effects are concerned, is the same as if the waves were in the same phase. We have thus to combine two waves that are in the same phase, the displacements in which are so related that one is represented by UR and the other by the exactly equal and *opposite* RU. Clearly these two displacements annul one another, so that the color corresponding to this particular wave-length is totally absent from P_1. As everything is symmetrical round the axis, this absence of color will apply to all points on a circle whose radius is QP_1 and center is Q, so that there will be a dark circle round the axis. The argument will apply

equally well to a point P_2 so chosen that the phase difference is two wave-lengths, or to P_3, where it is three wave-lengths, and so on. Thus there will be a whole series of circles round the axis, which will be dark as far as the color corresponding to this wave-length is concerned.

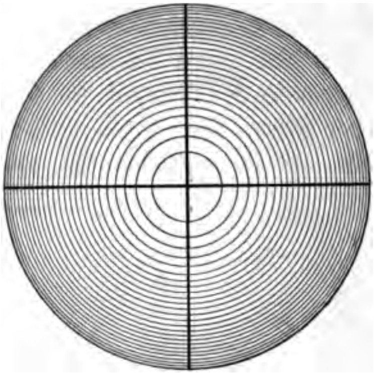


FIG. 56

These concentric circles will not, however, be the only dark regions of the field of view. Consider any point P (Fig. 54) on the line QN_1. The only displacement at such a point that the first Nicol will permit to pass must be in the direction QN_1, and as this is at right angles to QN_2, the corresponding wave will not be able to get through the second Nicol. There must, therefore, be complete darkness at P, and so for any other point on lines in the directions QN_1 and QN_2. Hence, we should expect to see a series of dark circles round the axis, with a black cross whose arms are parallel to the directions QN_1 and QN_2 such as is represented in Fig. 56.

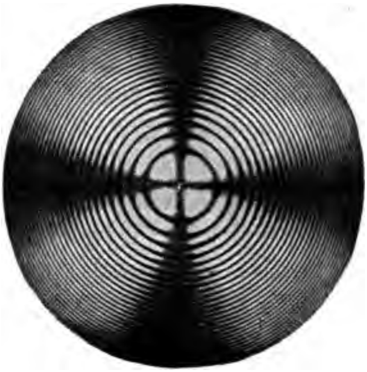


FIG. 57

The difference of phase for the two waves that traverse

the crystal depends on the velocities of these waves, and so is different for waves of different length and color. Thus, the points P_1P_2... will have slightly different positions for the different colors that go to make up white light, and if the incident light be of this character, the rings will be colored, giving the beautiful effect that you now see on the screen. Figure 57 is from a photograph of what actually appears, unfortunately, however, robbed of all the beauty of color. You will observe that the *darkest* part of the field corresponds exactly with the cross and rings predicted from theory and indicated in Fig. 56.

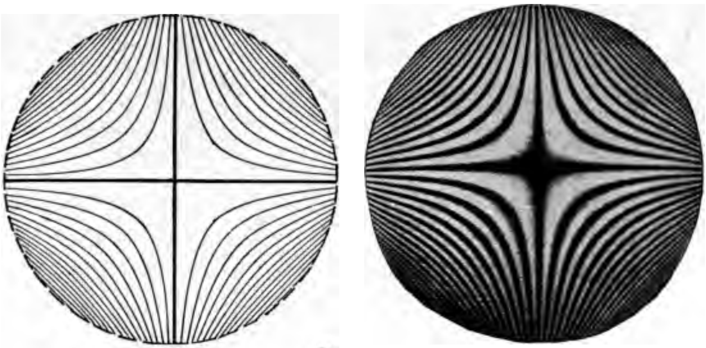
We have been dealing with the case in which the two Nicols are "crossed." Suppose, now, that we turn the second Nicol through a right angle, so that QN_2 of Fig. 54 coincides with QN_1, and consider in what way this should modify the results. As before, the displacement represented by P_1R is equivalent to a combination of P_1U and UR (Fig. 55), but of these it is the second that is now annulled by the second Nicol, so that when this wave gets through the apparatus the displacement in it is represented in magnitude and direction by P_1U. In the other wave the displacement RT is again equivalent to RU combined with UT, and the first of these is annulled by the second Nicol, so that UT represents the displacements in the emergent wave. Thus the displacements in the two waves are in the same direction, and being effectively in the same phase, their combined effect is additive, and instead of darkness we have brightness. Thus, where formerly we had a series of dark rings we should now expect a complementary series of bright ones. The cross, too, instead of being black, will be bright. For if we take

a point such as P on QN_1, the first Nicol confines its displacements to the direction QN_1, and these pass freely through the second Nicol, and this is true also for a point on a line at right angles to QN_1. Thus we have brightness all along two lines at right angles, as you see from Fig. 58, which represents the actual state of affairs, except, as before, for the color.

Fig. 58

In dealing with these phenomena of rings and crosses, I have attempted merely to indicate the general character of the results that are to be expected and that are actually found to occur. With the aid, however, of the theory of wave propagation in a crystal, it is not difficult to predict more of the details of the phenomena, such as the size and relative intensity of the rings as well as their form. A very great number of arrangements of the crystalline plate and the Nicols have been examined, both from the theoretical and the experimental point of view, and the agreement between the two is thoroughly satisfactory at all points. We have dealt only with the simplest case that can present itself, that of a uniaxal crystal cut at right angles to its optic axis, with the axis of the incident light in the same direction as the optic axis. The results, of course, are more complex with crystals of a less simple form, and it may suffice to refer very briefly to a few other cases.

Let us take first the case of two thin plates of the same material and thickness, both cut with their faces parallel to their optic axes, and held together with their axes at right angles to one another. Theory shows that in this case we should again see a dark cross, and that the other dark lines in the field should be a series of rectangular hyperbolas such as are represented in Fig. 59 *a*. This

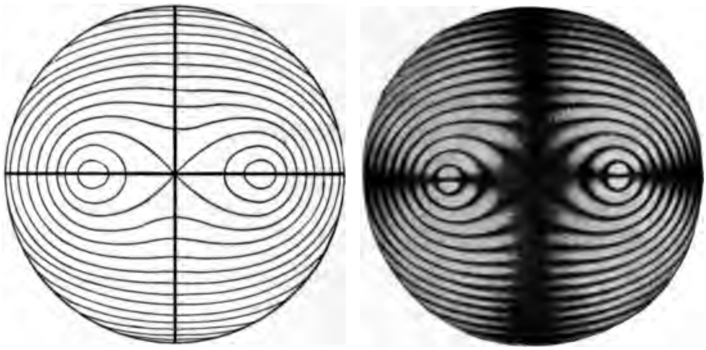


(*a*) FIG. 59 (*b*)

figure shows the darkest portion of the field according to the theory, while Fig. 59 *b* is from a photograph of what is really seen.

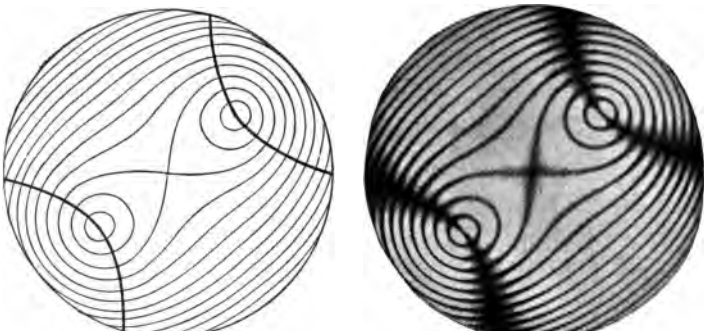
Consider next a thin plate cut from a biaxal crystal, with its faces at right angles to the bisector of the angle between the optic axes. Put this plate between a pair of crossed Nicols, and turn it so that the line joining the ends of the optic axes is parallel or perpendicular to the "principal planes" of the Nicols, *i.e.* is parallel to lines such as QN_1 or to QN_2 of Fig. 54 *b*. If a beam of light like that used before now fall upon the plate, we should expect alternations of light and darkness. Investigation shows that a black cross is to be looked for in this case

as before; but the other dark lines in the field will no longer be circles or hyperbolas. Their form is easily deter-



(*a*) FIG. 60 (*b*)

mined from theory, and it appears that they belong to a class of curves known as lemniscates, whose foci are at the ends of the two optic axes. Figure 60 *a* shows the lines



(*a*) FIG. 61 (*b*)

drawn through the *darkest* part of the field, according to the predictions of theory. Figure 60 *b* is from a photograph of what is actually seen (except, once more, for the

color), and by comparing these two figures you will see that there is an excellent agreement.

Lastly, let us turn the crystalline plate through an angle of 45° from its last position and see the change that takes place. The lemniscates should appear, as before, but turned through half a right angle; and there should be no black cross, its place being taken by a dark hyperbola going through the ends of the optic axes. The *darkest* part of the field, according to theory, should appear as in Fig. 61 *a*, and this should be compared with the neighboring figure (61 *b*) from a photograph of the actual appearance. These various figures give no idea of the beauty due to the scheme of color; but they may serve their purpose of bringing home to you with what accuracy theory enables us to foretell what is to be expected under any given circumstances, and to account for all the details of the phenomena that have been observed.

IX

DIFFRACTION

Suppose you throw a stone into water at S (Fig. 62), and watch what happens. A circular wave will travel out over the surface of the water in all directions. At one time the crest of the advancing wave will be at OP; a little later it will have moved on to EQ. How is this effect produced? The impact of the stone causes a disturbance at S, an up-and-down motion of the water there, and this is communicated to the neighboring particles. Each particle hands on the disturbance to its neighbor; but in what way does it hand it on? It *looks* somewhat as if the disturbance could be passed along only in *one direction.* P seems to pass on its motion only in the direction Pa, forwards towards Q, and not backwards toward S, or laterally along Pb or Pc or Pd. If this were so, it would appear to explain some of the phenomena. Thus, it would explain why there is no disturbance behind OP (in the direction toward S), and in the case of waves of light — and it is, of course, with the analogous problem in light

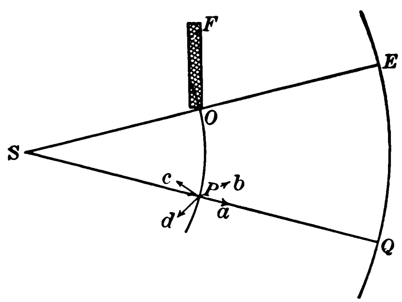


Fig. 62

that we are interested — why, if we put a screen in the position *OF*, we appear to get a sharply defined shadow extending to *E*, where *SOE* is a straight line. This familiar phenomenon of shadows gave rise to the idea that light moves in straight lines, and, as we have seen, the law of the rectilineal propagation of light was one of the few general laws of optics that were known to the world in pre-Newtonian days. The only objection to the law is that it is not true. Light does *not* move in straight lines, and the shadow of an obstacle is not sharply defined by drawing straight lines from the source of light to the edge of the obstacle. Closer examination reveals the fact that light bends round a corner. This phenomenon was sometimes spoken of as the *inflection* of light, but is now always referred to as *diffraction*.

When we look into the question of the amount of bending round a corner, and discuss it by means of the principles to be referred to later, we find that the bending depends very largely on the length of the wave, short waves being much less bent than long ones. This dependence of the bending on the wave-length is so important that it may be well to make an experiment to bring it home to you. In ordinary speaking you set up waves in the air, and you know that these must bend freely, as you can easily hear a person who is speaking round a corner. The length of the waves that are thus set up by speech depends on the pitch of the voice, but we may say that normally they are four or five feet long. In my hand I have a whistle that will produce very much shorter waves than that. As it is now arranged it sends out waves about four inches long, and by altering its mechanism I can make the waves shorter and shorter. If one of you

were to go behind that large screen, and listen carefully while I sound the whistle, you might be able to determine whether there is anything resembling a sound shadow or not. It will be better, however, to arrange things so that all can observe the phenomena together. We can do this easily by aid of this sensitive flame that you can all see, and that will serve just as well as an ear (indeed, better than that in some respects) to detect the presence of a wave in the air. The manner of producing this sensitive flame need not concern us at present, all that need be known being that it is sensitive — you observe that the flame ducks when I blow this whistle and the disturbance in the air strikes it. For our purposes this flame has the important advantage over the ear that it can be made sensitive to waves that are too short to produce the sensation of sound. It has already been pointed out that the eye is sensitive only to waves whose lengths lie within a certain range, and the same is true of the ear. Very high notes and very low notes cannot be heard, as they do not affect the ear in the right way, and it should be remembered when watching this experiment with the whistle and the flame that very high notes are very short in wave length. As I alter the effective length of this whistle, you can hear that the note it emits gets shriller, and now that the wave is so short that you hear no note at all, there is, as you see, a somewhat sharply defined shadow of the screen. You observe that when I move the whistle very slightly to the right or to the left of a line joining the sensitive flame to the edge of the screen, there is a perceptible difference in the effect. In one case the flame is inside the shadow, and is unaffected of the waves in the air; in the other it responds to the action of these waves. You see, then,

that although an ordinary sound-wave bends readily round a corner, there is scarcely any bending perceptible when the length of the wave is sufficiently short.

This problem of the bending of light round a corner has presented difficulties almost from the beginning of modern science. Newton knew some of the phenomena quite well, but he did not observe them closely enough to grasp all that was significant, and his failure to do so led him seriously astray. He knew that the shadows of bodies are bordered with colored fringes. He knew also that if the light from a small source falls upon a body, the shadow is not exactly coincident with the *geometrical shadow*, as it is sometimes called, *i.e.* the figure formed by drawing *straight* lines from the source of light past the edge of the opaque body and observing where these lines are interrupted by the plane on which the shadow is cast. Thus, in his first observation on "The Inflexions of the Rays of Light," in the third book of his "Opticks," he tells us that he let light stream through a pinhole in a piece of lead and fall upon various objects, and he then observed that "the shadows were considerably broader than they ought to be, if the rays of light passed on by these bodies in right (*i.e.* straight) lines. And particularly a hair of a man's head, whose breadth was but the 280th part of an inch, being held in this light, at the distance of about 12 feet from the hole, did cast a shadow which at the distance of 4 inches from the hair was the 60th part of an inch broad, that is, about four times broader than the hair." In this case there seems to be a bending *away* from the shadow and not into it. This puzzled Newton, and seemed to him so incompatible with a wave theory of light that he rejected that theory. Listen to what he says in one of his famous

queries at the end of his book on optics. "Are not all hypotheses erroneous in which light is supposed to consist in motion propagated through a fluid medium? If it consisted in such motion, it would bend into the shadow. For motion cannot be propagated in a fluid in right lines beyond an obstacle which stops part of the motion, but will bend and spread every way into the quiescent medium which lies beyond the obstacle. The waves on the surface of stagnating water passing by the sides of a broad obstacle which stops part of them, bend afterwards, and dilate themselves gradually into the quiet water behind the obstacle. The waves of the air, wherein sounds consist, bend manifestly, though not so much as the waves of water. But light is never known to follow crooked passages nor to bend into the shadow. For the fixed stars, by the interposition of any of the planets, cease to be seen. And so do the parts of the Sun by the interposition of the Moon, Mercury, or Venus. The rays which pass very near to the edges of any body are bent by the action of the body; but this bending is not *towards* but *from* the shadow, and is performed only in the passage of the ray by the body, and at a very small distance from it. So soon as the ray is past the body it goes right on." Had Newton varied his experiments, and observed carefully enough, he could have found a bending *towards* the shadow, as we shall see later. Here, then, we have a striking case of a very great scientist being led astray, and, as we now see it, very seriously astray, by *experimental* evidence. Snares seem to be laid along every path, and we may be entrapped by experiment just as well as by theory. There are so many warnings up along the latter road that there s not the same excuse for falling. And yet men fall, as

Brewster did not so very long ago, if Tyndall reports him fairly. "In one of my latest conversations with Sir David Brewster, he said that his chief objection to the wave theory of light was that he could not think the Creator guilty of so clumsy a contrivance as the filling of space with ether in order to produce light." Such a high *a priori* road is probably the most dangerous of all.

To return to the problem of diffraction, there is by this time not the slightest doubt that light does bend round a corner. As we shall see presently, we have many careful determinations of the amount of bending and of various details of the phenomena. With the refinements of modern instruments at our disposal, it is comparatively easy to deal with these matters experimentally; but when we come to examine them from the standpoint of theory, a number of difficulties arise. The form that the problem takes in the mind of a mathematical physicist is something as follows. A given disturbance is set up in the ether by the presence of a source of light. This spreads out in a known manner, and there is no special difficulty in calculating and predicting all the details of the phenomena to be observed, provided that no opaque obstacle is present. Suppose, however, an opaque body is put in the way of the waves in the ether. How does this affect the motion of the waves in the region beyond the body? The physical and mathematical conditions to be satisfied are easily stated. We know the disturbance in the neighborhood of the source, and we know the conditions to be satisfied at all points of the boundary of the opaque obstacle. It looks as if everything that we want should be within our powers of computation, and in other fields many similar problems have been successfully attacked. In the case of

optics, however, peculiar difficulties present themselves owing to the extreme shortness of the waves of light, and these difficulties have not as yet been successfully overcome, except in a few very special cases. In general, the complete solution of the optical problem of diffraction still awaits us. I trust that you do not misunderstand me here. It is not the case that there is any special difficulty with the general *theory*, nor any apparent discrepancy between theory and observation. The difficulty that I speak of is purely one of *mathematical analysis*, and arises entirely from the limitations of our skill in that branch of art. Doubtless it will be overcome in time.

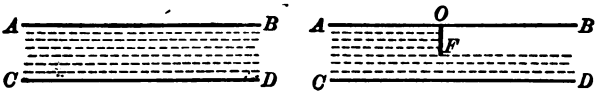
Meanwhile we are constantly reminded that "Nature is not embarrassed by difficulties of analysis," and that, in our interpretation of Nature, we must not allow such difficulties to embarrass us unduly. Thus, in the present case, although a rigorous mathematical solution is as yet unattainable in general, it may be possible to get an approximately accurate solution which is good enough for practical purposes. As a matter of fact, this has already been done, and the results are found to be as accurate as we need in the present state of our experimental skill. Thus the difficulties of mathematical analysis to which reference has been made may very properly be handed over to our successors, whose finer instruments and more accurate observations may demand a correspondingly refined analysis. The method that is generally adopted in dealing with such problems to-day is to make use of what is known as the *Principle of Huyghens*. Let us look once more at Fig. 62, with which we dealt at the outset of this lecture. A disturbance was set up at the point S, and from this point waves traveled out *in all directions*. If this

be true of the point S, we should expect it to be true for any other point that is disturbed; whether the initial disturbance be set up by a stone or some other agent can make no difference, and there is nothing peculiar to S, except that it happened to be the point that was disturbed first. Hence, any other point, such as P, must be regarded as a center of disturbance from which waves proceed *in all directions*. The Principle of Huyghens merely states that each point of the front of an advancing wave may be regarded as a center from which secondary waves spread out, not in one direction, such as Pa, but in all directions. What will be the effect of the combination of all the secondary waves thus set out is a question to be answered by the help of the Principle of Interference, which makes it clear that the effect will depend on the amplitudes and phases of the various secondary waves that have to be considered. To determine exactly what is the law governing these features of the secondary waves is a difficult problem. It was attacked by Stokes in a famous memoir "On the Dynamical Theory of Diffraction." In this the problem was to determine what must be the amplitudes and phases of the secondary waves, so that in combination these waves would give the actual disturbance in front of the advancing wave and no disturbance at all behind it. Interesting and instructive as was Stokes's discussion of this problem, his solution has not escaped criticism. Amongst other things it has been pointed out that the problem is really an *indeterminate* one. The question asked is one that can have several answers, like the question, What two integers, when added together, make 6? and there is nothing to determine which of the answers is to be preferred. Various laws have been sug-

gested other than the one that Stokes arrived at, and it should be noted that, while differing in other respects, they agree as to the disturbance produced by the secondary waves in the only region where these waves are really effective, *i.e.* in the neighborhood of the direction PQ. The waves that travel in all other directions have their influence neutralized through interference with other waves. If, then, we wish to estimate the effect of all the secondary waves that pass over Q, it appears that we need consider those only that set out from the wave-front *OP in the neighborhood of P*. It is for this reason that PQ is sometimes spoken of as the path of the *effective* disturbance that passes from P to Q, and this effective disturbance constitutes the *ray of light*.

Let us suppose, now, that a screen OF is interposed so as to interfere with the advance of the waves in the ether. How will this affect the propagation of the waves and the optical phenomena in the region beyond the screen? This is a hard question to answer, owing, as has been explained, to the mathematical difficulties that arise in its discussion. These difficulties have been completely overcome only in one or two special cases, but an approximate solution has been reached in many others. To obtain this, an assumption is made that is certainly not justified if we insist on absolute rigor and exactness throughout. Such a lofty attitude, however, makes progress impossible, and as practical men we prefer to make some advance, even by means of an unjustifiable assumption, provided we have reason to suppose that this assumption will not lead us too far astray. The assumption made is that the effect of the screen is merely to destroy the secondary waves that, but for its presence, would be

propagated from the various points of its surface, while all the other secondary waves from points not on the screen go forward just as if the screen were away. It is easy to see that this cannot be quite strictly true. Consider the simple case of a stream of water flowing in a closed space between two horizontal boards represented in section by *AB* and *CD* in Fig. 63 *a*. Each particle would move horizontally, along lines such as the dotted ones



(*a*) (*b*)

FIG. 63

of the figure. Now put in an obstacle, such as *OF* in Fig. 63 *b*. This would do more than merely stop the onward rush of the drops of water that struck the obstacle. It would affect the motion in the neighborhood of *F*, and the motion below and to the right of that point in Fig. 63 *b* would *not* be just the same as at the corresponding point of Fig. 63 *a*. In the case of waves it appears, however, on investigation, that the error introduced by this assumption is inappreciable except within a few wave-lengths of the edge of the obstacle. We shall see before the close of this lecture that there are something like 50,000 wave-lengths of light to the inch, and owing to this extreme shortness, the region of error due to the false assumption is so small as to be practically negligible. Proceeding, then, with this assumption, we are able to compute all the essential details of the optical phenomena in a large number of interesting cases, and in many of these to test our (admittedly imperfect) theory by comparison

with the most careful measurements that are available. This was first done by Fresnel in a classical memoir on Diffraction that was crowned by the French Academy in 1819. Fresnel considered the case of light falling on an opaque screen with a straight edge. If the light were propagated strictly in straight lines, there would be a sharply defined shadow, coinciding with the geometrical shadow, the contour of which is determined by drawing

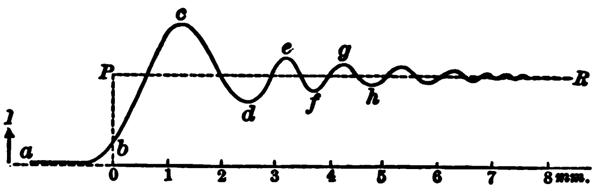


FIG. 64

straight lines from the source of light to the edge of the screen. Inside this shadow there would be absolute darkness, and outside it uniform brightness. The curve of intensity would then be the dotted curve of Fig. 64. In this O represents the position of the edge of the geometrical shadow, the shadow being to the left of O. OP represents the intensity of the incident light, as well as that in the bright part of the field at some distance from the edge of the shadow. Fresnel showed that the theory that has just been sketched would lead us to expect a distribution of light that is indicated by the continuous line of the figure (*abcde*...). It will be observed that there is no longer complete darkness to the left of O, but that the light fades away rapidly as we go into the shadow. Perhaps the most striking result of the investigation is that outside the shadow (to the right of O in the figure) the intensity of

the light is not uniform, but that there are a series of bright bands where the intensity is much greater than the average (*c*, *e*, *g*...), alternating with bands where it is much less (*d*, *f*, *h*...). The theory indicates, and this is fully confirmed by experience, that the exact distribution of light depends on the wave-length of the incident beam. Fresnel calculated the details for red light of wave-length 0.000638 millimeters or 0.000025 inches. The intensity of the light at the brightest bands, corresponding to *c*, *e*, *g*... of Fig. 64, when expressed in percentage of the intensity of the incident light, was found to be 137, 120, 115, 113, 111, 110, 109..., and that at the intermediate darks bands (*d*, *f*, *h*...) to be 78, 84, 87, 89, 90, 91, 92... Owing to the difficulty of making very accurate measurements of intensity, it was not easy to make a searching test of the theory by comparing these results with those derived from experiment. There is, however, another feature that is more easily measured with accuracy, and that is the distances of the different fringes from the edge of the geometrical shadow. The following table gives the positions, obtained from theory and also from observation, of the first five dark bands for the red light used by Fresnel. The results are set out for three different distances (*d*) of

	$d = 100$		$d = 1011$		$d = 6007$	
	Theory	Observation	Theory	Observation	Theory	Observation
First Fringe . .	2.83	2.84	2.59	2.59	1.14	1.13
Second Fringe .	4.14	4.14	3.79	3.79	1.67	1.67
Third Fringe. .	5.13	5.14	4.69	4.68	2.07	2.06
Fourth Fringe .	5.96	5.96	5.45	5.45	2.40	2.40
Fifth Fringe . .	6.68	6.68	6.11	6.10	2.69	2.69

the screen from the source of light. All the distances are given in millimeters, and you will remember that one millimeter is equal to 0.03937 inches. It will be seen that the agreement between theory and observation is excellent. The position of the bright bands depends upon the wave-length, and so on the color of the light. If, then, we employ a mixture of colors such as constitute white light, we shall get a series of colored fringes in slightly different positions. These will tend to overlap one another, and the overlapping will make it difficult to distinguish the outer bands of color. Hence, for accurate measurements designed to test any theory, it is expedient to use homogeneous light, and so have only a single wave-length to deal with.

The same general method will enable us to discuss the phenomena to be looked for in various other circumstances. Thus, instead of dealing with a single straight edge, we may wish to examine the effect of two parallel edges close together constituting a narrow slit. The simplest apparatus to use for such experimental purposes is your own hand. Hold two fingers together so that they are very nearly closed, and look through the narrow opening at a distant bright object. You will see a number of colored fringes, but if you wish to investigate the phenomena carefully, it will be better to take a little more trouble and proceed as follows. Cut a slit about an eighth of an inch wide in a black card and fix this in front of a bright light. Look at this slit through the narrower slit made by drawing with the point of a needle a straight line on a piece of blackened glass, and hold the two slits parallel to one another. You will at once observe a series of colored spectra. If you make the light homogeneous by interposing, say, a red glass between the light and the

first slit, you will see a series of bright red bands, R_1 R_2... (Fig. 65), on each side of the central image R, and you will notice that their intensity diminishes as you get further away from the central band. On replacing the red by blue, you will observe a similar effect, but the bright blue bands will be narrower and closer together than were the red, as is indicated roughly in the figure by the positions of the rectangles B, B_1... You see from this that if both colors are present together, the different bands will overlap, and you will understand the various spectra that

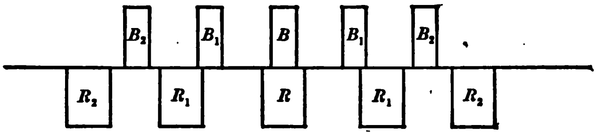


FIG. 65

are seen when white light is employed. By fixing a narrow slit on the end of your opera glasses, you can readily see these spectra and examine their details at your leisure.

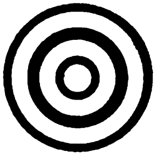
Closely allied to the case of a narrow slit is that of a narrow obstacle placed in the path of a beam of light. Reference has already been made to Newton's experiment with a human hair, which exhibits the phenomena. You can easily see this for yourselves by partially closing your eyes and looking at a bright light through your eyelashes. A fine wire is now placed in front of the lantern, and you observe that the dark shadow on the screen is bordered with colored fringes, and now that a mesh of wires is substituted for the single wire, you see that the color effects are quite gorgeous. The effects to be expected from apertures and obstacles of various forms have been carefully examined both theoretically and experimentally, and

the agreement between theory and observation is, on all points, most satisfactory. We have time only to select a single example, that of a circular aperture (and the corresponding case of a circular obstacle). This is especially important, owing to the fact that most optical instruments (telescopes, microscopes, and the like) are arranged so that the light passes into them through a circular aperture. The mathematical analysis of the case is long and somewhat complex, but the fundamental principles employed are the same as those that have already been explained. The investigation shows that where light shines through a circular aperture upon a screen, the screen is not uniformly illuminated, but that there are marked variations in the intensity at different portions of the circular patch of light. The points where the brightness is least constitute a series of concentric dark rings whose radii can be determined from theory, and, of course, observed experimentally. The sizes of these rings depend on the color of the light, so that when white light is employed, the screen exhibits a series of colored rings. Lommel made careful determinations of the radii of these rings for various colors, and compared his observations with the deductions from theory. The results for the first four dark rings are set out in the table below for a few cases, but Lommel dealt with over 180 such cases, and in all of these the agreement between theory and observation was as good as in those here selected. The different colors used were red, orange, green, and blue, corresponding to the spectral lines known as C, D, E, and F and to wavelengths of 0.0006562, 0.0005889, 0.0005269, and 0.0004861 millimeters. The radius of the aperture was 0.28, the distance of the edge of the aperture from the source of

light was 2120, and of the source of light from the screen, 2210.4. These numbers and those in the table all represent millimeters.

Blue		Green		Orange		Red	
Theory	Observation	Theory	Observation	Theory	Observation	Theory	Observation
0.015	——	0.032	0.034	0.057	0.056	0.082	0.082
0.156	0.158	0.179	0.175	0.308	0.305	0.237	0.231
0.254	0.254	0.275	0.276	0.403	0.406	0.343	0.338
0.333	0.333	0.361	0.361	——	——	0.449	0.451

Theory also enables us to calculate the intensity of the light at different positions on the screen. It thus appears that about 84 per cent of the whole light is inside the first dark ring. The central spot is not, however, of uniform brightness, but shades off as we proceed outwards from the center, the intensity halfway between the center and the first dark ring being about 37 per cent of that at the center. Perhaps the most important result to bear in



(*a*)

(*b*)

Fig. 66

mind is that the image of a point is not a point, but a complicated system of rings of the kind indicated roughly in Fig. 66 *a*. Figure 66 *b* represents the image of two points close together, and shows how the two images tend

to overlap and produce a blurred effect. Fortunately, most of the light is confined within the first ring, so that we do not go far wrong in supposing that the image of a point as seen through a telescope is a small disk. Do what we will, however, we cannot make this disk shrink to a point, and when we take a photograph we set the light the difficult problem of drawing a clear picture with a blunt pencil. The bluntness of the pencil depends upon the diameter of the little disk of light, and to sharpen it as much as possible we must increase the size of the aperture and use light of the shortest wave-length that can be employed. Fortunately, for photography, the short waves have great actinic power; but the other requirement, that of a large aperture, is not so easily satisfied and, as it involves great size, adds seriously to the cost of the best telescopes used for astronomical purposes.

The corresponding problem presented by the shadow of an opaque disk was also solved by Lommel. Here, too, we have a series of alternations of light and darkness, giving the appearance of a number of concentric rings with their center at the center of the shadow. The table below gives the radii of the first four dark rings in a few cases; but Lommel dealt with over sixty cases in all, and found the same good agreement between theory and observation.

Blue		Green		Orange		Red	
Theory	Observation	Theory	Observation	Theory	Observation	Theory	Observation
0.088	0.090	0.096	0.096	0.109	0.113	0.119	0.124
0.200	0.197	0.219	0.220	0.242	0.237	0.268	0.265
0.307	0.310	0.335	0.333	0.369	0.367	0.403	0.400
0.406	0.406	0.438	0.440	0.478	0.479	0.525	0.525

Here the radius of the disk was 0.32, and the distance of its edge from the source of light was 1485. Observations were made with the four colors previously mentioned, — blue, green, orange, and red, — the distance of the screen from the source of light being 1639.9, 1642.6, 1643.3, and 1643.2 for the different colors. All the numbers represent millimeters. The different radii for the different colors give an idea of the amount of overlapping when white light is employed, and of the arrangement of the colors in the fringes. In this case also theory enables us to calculate the intensity of the light at different points in the shadow. In this connection one feature may be pointed out, as it is probably unexpected. It appears from the investigation that at the very center of the shadow there should be a bright spot, and that this should be just as bright as if there were no disk present to cut off the light. This deduction seemed so absurd when it was first announced that it was regarded as a serious objection to the wave theory. A little care, however, in experiment showed nevertheless that, however unexpected or seemingly impossible, it was none the less perfectly true. If you have the resources of a physical laboratory at your disposal, you will find no great difficulty in trying this for yourself. You will need a carefully made circular disk that is not too large, and you will need to make the necessary adjustments with some precision. I will modify the experiment so as to exhibit the result to the whole audience and deal with sound-waves rather than with light, so as to work on a larger scale. The mathematical analysis is very similar in the two cases, but the sound-waves have the advantage of being much longer, so that we do not need the same refinement. Introducing you once more to this

whistle and sensitive flame, I fix a circular disk of glass, about a foot in diameter, between the two. By moving the whistle into different places, you observe that there is a marked sound shadow behind the disk; but now that, after some adjustment, I have got the whistle so that it is exactly opposite the center of the disk, you see that the flame ducks, and by doing so indicates the presence of a considerable disturbance in the air.

The applications of the theory of diffraction to the construction of optical instruments and to the explanation of various optical phenomena are so numerous that it would be impossible in the time at our disposal to deal with them at all adequately. In the short time that remains to me for this lecture I shall endeavor to explain very briefly how it is that the principles of diffraction enable us to measure the lengths of different waves of light and to measure them with wonderful accuracy. Several methods may be employed for this end, but I shall confine myself to what is the simplest for purposes of exposition. This measures the wave-lengths by the aid of a *diffraction grating,* an extremely simple instrument as far as its appearance is concerned. It is made by ruling a great number of very fine parallel lines on speculum metal or glass. The former is viewed by reflection, as the metal reflects a large proportion of the incident light, and is called a *reflection grating.* The glass reflects some light, and usually transmits more. If viewed by transmission, *i.e.* if the incident light be allowed to stream through the grating and the transmitted beam be then examined, the arrangement is described as a *transmission grating.* In either of these cases the effect of the grooves made by ruling is to scatter irregularly the light that falls on them,

so that the grooves behave as if they were opaque and destroyed the light that strikes them. Let us consider light falling normally on a transmission grating, a cross-section of the surface of which is represented in Fig. 67. The thick lines in this figure, such as x_1a_2, x_2a_3..., show the positions of the grooves, which, as we have just seen,

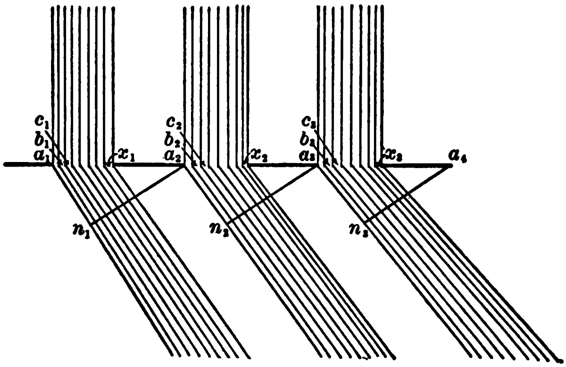


Fig. 67

practically stop all the light that falls on them. Waves enter the instrument through the portions a_1x_1, a_2x_2..., and if we consider a_1x_1 as the front of an entering wave, then every point on this front is to be regarded (as was stated earlier) as a center of disturbance from which waves, and therefore rays, spread out in *all directions*. If the front of the incident wave were complete, that is, if there were no obstructing grooves, the waves that spread out laterally in any such direction as a_1n_1 would be nullified by interference with the waves that proceed from other portions of the wave-front, and it would only be directly in front of a_1 that the effective disturbance would be appreciable. The grooves, however, cut out some of the waves that

would contribute to this interference. This must modify the results, so that it may well be that there is an appreciable disturbance in some such direction as a_1n_1.

To investigate this matter more fully, we must bear in mind the fundamental idea that lies at the root of the Principle of Interference; namely, that two waves that are similar in all other respects, but that differ in phase by half a wave-length, or *any odd multiple thereof*, will interfere and produce darkness, while if they differ in phase by a whole wave-length, *or any multiple thereof*, they reinforce one another and give greater intensity of light. Let us consider all the secondary waves that travel outward from the various points of the incident wave-front in a given direction, such as a_1n_1 (to which a_2n_2 and a_3n_3 in the figure are parallel). The difference of phase between the waves from a_1 and a_2 is represented by a_1n_1; where a_2n_1 is perpendicular to a_1n_1. This will also be equal to the difference of phase between the waves from b_1 and b_2, provided a_2b_2 be equal to a_1b_1. Now *if the grooves be of exactly the same width, and the spaces between them be equal*, it will be possible to divide all the spaces into the same number of equal parts, so that $a_1b_1 = b_1c_1 = \ldots = a_2b_2 = b_2c_2 = \ldots = a_3b_3 = b_3c_3 = \ldots$. We shall also have $a_1n_1 = a_2n_2 = a_3n_3 = \ldots$, and the difference of phase between the secondary waves from a_1 and a_2 will be the same as between those from b_1 and b_2 or from c_1 and c_2, or from a_2 and a_3 or from b_2 and b_3, and so on. Let us suppose, further, that the incident light is homogeneous, *i.e.* all of the same wave-length, and that a_1n_1 is half this length. Then if all the secondary waves could be brought together without relative change of phase, the wave from a_1 would interfere with that from a_2, the wave from b_1 would interfere with that from b_2, and

so on, thus producing darkness in the direction a_1n_1. The combination of the different secondary waves is simply effected by means of a lens, which bends the rays so as to bring them to a focus, and alters the direction of the wave-motion without changing the relative phase of the different waves. Let, then, OA in Fig. 68 represent one of the lines in the grating, and OB a line drawn at right angles to the plane of the grating to meet a screen, on which the light falls, at B. If OD_1 be drawn in the direction represented by a_1n_1 in Fig. 67, and D_1D_1' be drawn on the screen parallel to OA, then from what has been said it will be seen that D_1D_1' will coincide with a dark line on the screen.

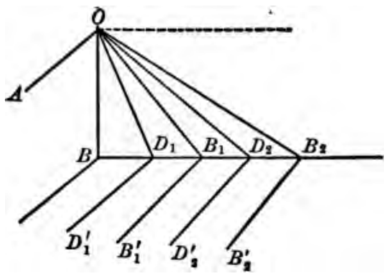


FIG. 68

This, however, will not be the only dark line, for the same interference will take place when a_1n_1 is equal to any odd multiple of half a wave-length as when it is simply half a wave-length. If OD_2, OD_3,... be the directions corresponding to phase difference of three half wave-lengths, five half wave-lengths, and so on, then there will be dark lines D_2D_2', D_3D_3',..., all parallel to OA. We have dealt with the case where a_1n_1 is half a wave-length or any odd multiple thereof. Let us suppose next that a_1n_1 is a wave-length, or any exact number of wave-lengths. Then the various secondary waves, instead of interfering, will reinforce one another, and the corresponding portions of the field will be unusually bright. We shall thus have a series of bright lines, such

as B_1B_1', B_2B_2',..., in Fig. 68. On comparing the triangle $a_2n_1a_1$ of Fig. 67 with OBB_1 of Fig. 68, it is seen that these triangles have equal angles. The angle $a_2n_1a_1$ is equal to the angle OBB_1, as each is a right angle, and the angle $n_1a_2a_1$ is equal to the angle BOB_1, since OB is perpendicular to a_1a_2, and OB_1 is parallel to a_1n_1, and therefore perpendicular to n_1a_2. As the two triangles have equal angles, it follows geometrically that they must be similar triangles differing only in *scale*. Hence the ratio of a_1n_1 to a_1a_2 must be equal to the ratio of BB_1 to OB_1, or, in algebraic symbols, $\frac{a_1n_1}{a_1a_2}=\frac{BB_1}{OB_1}$. Thus we have $a_1n_1=a_1a_2\times\frac{BB_1}{OB_1}$. Now a_1a_2 can be measured accurately by counting the number of grooves in a given distance. Thus, if on the grating there are twenty thousand lines to the inch (there are more than this on many good gratings), then a_1a_2 is one twenty-thousandth of an inch. The distances BB_1 and OB_1 might be measured directly, but it is only their ratio that is wanted, and this can be determined most simply and accurately by the aid of trigonometry, once the angle BOB_1 has been measured. The measurement of this angle can be made with great precision and then, from the equation $a_1n_1=a_1a_2\times\frac{BB_1}{OB_1}=a_1a_2\sin BOB_1$, the quantity a_1n_1 is readily calculated. It has been indicated, however, that this quantity a_1n_1 is the wave-length of the light with which we are dealing, so that the problem of determining the wave-length has been solved.

If the process thus sketched be carried out carefully with a good grating, the wave-lengths may be determined with marvellous accuracy. There are several ways of testing the results. Thus, if we deal with the bright line

B_1B_1', the calculated value of a_1n_1 should be the wave-length. If we make similar measurements with B_2B_2', then the corresponding value of a_1n_1 should be *twice* the wave-length; with B_3B_3' it should be *thrice* this length, and so on. The consistency of the various estimates of the wave-length thus obtained will enable us to form an estimate of the accuracy of our results. Then, too, we need not confine our attention to the case of light that strikes the grating at right angles to its surface. This case has been dealt with and illustrated in order to simplify the mathematical discussion as much as possible; but it requires a very slight effort to extend the argument to the more general case of oblique incidence and to obtain a corresponding formula for the wave-length. By making observations at various angles of incidence and computing the wave-length, we have other means of testing the consistency and accuracy of our results, and when all precautions are taken, it is found that these results are marvellously concordant. For this end, of course, a good grating is indispensable, and a good grating is an instrument that requires great care and skill in the making. The rulings must be made with almost perfect accuracy, for the argument supposes that the distance between the various grooves and their width is uniform throughout, and if this be not the case errors will inevitably creep in.

There are other methods of measuring wave-lengths than the one here described, but time will not permit us to discuss them. Suffice it to say that few things can now be measured with such wonderful precision as the length of a wave of light. Such is the accuracy that has been attained, that it has been seriously proposed that the length of a wave of light emitted under certain condi-

tions from a specified substance should be adopted as the standard of length. This standard would have some advantages over any that are now in use, for all these are subject to slow and uncertain changes, and the one thing to be required of a standard above all else is that it should not change. The length of a wave of light emitted by a substance depends on properties of the ether and of the atom that, there is reason to believe, are invariable, so that this length seems capable of serving as a true standard. With this end in view Michelson devoted himself for some time to the problem of determining the length of the standard meter in wave-lengths. For this purpose he employed certain radiations from cadmium, which were chosen on account of their simple character. He found that the number of light-waves in the standard meter in air at 15° C and normal pressure was 1,553,163.5 for the red waves from cadmium, 1,966,249.7 for the green, and 2,083,372.1 for the blue, and that the measurements could be made so accurately that he could safely say that the errors were less than one part in two millions.

The following table gives some details with reference to wave-lengths and frequencies of the waves corresponding to different parts of the spectrum. The letters *A B C*... are the names by which these lines in the solar spectrum are known, and an indication of their color is given. The wave-lengths are expressed in millionths of a meter, and the frequencies in million millions per second.

Line of Spectrum	Wave-length in Millionths of a Meter	Number of Waves to the Inch	Frequency in Million Millions per Second
A	0.75941	33,447	395
B	0.68675	36,986	437
C (red)	0.65630	38,702	457
D (orange)	0.58930	43,102	509
E (green)	0.52697	48,200	569
F (blue)	0.48615	52,247	617
G (violet)	0.43080	58,960	696
H	0.39715	63,956	755

Before closing this lecture there is one feature of the phenomena observed when using a grating that must not be overlooked. We have seen that the position of the bright lines, such as B_1B_1', depends upon the length of the wave employed. It follows that, if the incident light be white, the bright lines corresponding to its various colored constituents will have different positions, so that instead of a single bright white line at B_1B_1', there will be a whole series of such lines forming a continuous spectrum, with all the colors of the rainbow, in the neighborhood of B_1B_1'. There will be a similar spectrum near B_2B_2', and so for the other lines, and to distinguish these various spectra from one another they are spoken of as spectra of the first order, second order, or third order, and so on, as the case may be. It was mentioned in the lecture on Spectroscopy that a prism was not the only means of producing dispersion and obtaining a spectrum, and we see now how this can be done by means of a diffraction grating. The spectrum produced by a grating has one great advantage over that formed by a prism in that the distances of the various colored lines from a certain fixed

line are proportional to the wave-lengths, as the above investigation shows. There are other advantages that cannot now be discussed, but we may say that for many purposes of accurate measurement, where a spectrum is involved, it is better to produce this spectrum by diffraction rather than by means of a prism.

X

LIGHT AND ELECTRICITY

SCIENCE has a vaulting ambition. It views the whole field of human knowledge and strives to possess it all. It sets about this tremendous task, however, in a business-like way and recognizes clearly that, for practical effectiveness, the beginning of wisdom is limitation. To attempt too much is to court failure, and, to avoid this, barriers have been placed across the field of knowledge, and individuals are advised to work strenuously within a little fenced-in portion of the whole field. It is well, however, occasionally to reflect that all the fences are artificial, and that they have been put up for practical purposes and for reasons that may not appeal to the more mature judgment of later generations. It is natural and convenient to fence off from one another things that seem to have little or nothing in common, but a deeper insight may reveal the fact that there is the closest relationship between what are apparently quite different things. The great divisions of natural science into Physics, Chemistry, and Biology are proving, after all, to be entirely artificial, and barriers between them are being broken down almost daily. And if this be true of the great divisions, it is true even more obviously of the subdivisions. In some cases it is difficult to find any traces to-day of barriers that in earlier ages seemed natural and inevitable. Thus, in one field you had to deal with what affects the ear and goes by the name of sound; in another your problem was to

discuss the mechanical properties of gases and the laws of motion within them. In the field of sound you learned to distinguish one sound from another by its intensity, by its pitch, and by its quality, and in process of time you established various laws of sound that enabled you to foretell the intensity, pitch, and quality of sounds emitted under various conditions. In the other field you found that waves could be set up in gases, and that these could be distinguished by their amplitude, by their frequency, and by their form, and you learned, by the aid of mechanical principles, to calculate the amplitude, frequency, and form of the waves set up in given circumstances. In time it seemed expedient to knock down the fence between the fields, for by postulating a relation between the intensity and the amplitude, the pitch and the frequency, the quality and the form, it was possible to explain all the peculiarities of sound on mechanical principles, and to test the theory by experiment in the most rigorous fashion that could be demanded. Thus to-day the problem of sound is regarded as a small part of the wider subject of vibrations (in air and other media), the vibrations being confined to narrow limits determined by the structure of the ear.

No two physical sciences seem, at first sight, more widely separated than light and electricity. My aim in this lecture is to show that they are in reality most intimately related. To this end let me begin by reminding you of the broadest outlines of the theory of light. We have seen that in order to coördinate the great mass of phenomena that have been observed in the field of optics, it is necessary to postulate the existence of a medium that we call the ether, and that we endow with definite

and peculiar properties. This ether is capable of transmitting disturbances by means of waves that travel through it with a speed that is determined by the properties of the ether, but that have frequencies depending entirely on the source of the disturbance. If the frequency be within certain limits that are determined not by the source of the disturbance but by the structure of the eye, the waves will produce the sensation of light. If, however, the frequency be higher than the limit set by the eye, then no light is seen; but the waves may show their presence in other ways, *e.g.* by their influence on a sensitive photographic plate. On the other hand, if the frequency be somewhat lower than this limit, the waves will produce the sensation of radiant heat, *and if it be very much lower, they will give rise to electrical phenomena.* Thus, from this point of view, the distinction between photographic action, light, radiant heat, and electricity is mainly a question of frequency, and light is seen to be only a small portion of the problem presented by the propagation of waves in the ether.

As a matter of history the science of electricity was built up quite independently of that of light. It soon appeared that to account satisfactorily for electrical phenomena it was necessary to postulate the existence of an ethereal medium, and in the process of time it became evident that exactly the same ether, with just the same peculiar properties, was required for electricity as for light. The idea of some such medium is a very old one in scientific speculation, but it was not until about seventy years ago that the great electrical researches of Faraday placed it as a leading article of faith in the creed of the scientist. About thirty years later came the epoch-making work of Clerk Maxwell. He was deeply imbued with Faraday's

ideas, but had the great advantage of being a skilled mathematician as well as a physicist. He set himself the problem of considering minutely the manner in which a disturbance would be propagated in the ether. Waves would be set up and would travel with a certain velocity, carrying certain electromagnetic effects along with them. In free space, where there is no matter and nothing but ether, this velocity would be independent of the frequency, and Maxwell showed that, if his theory were correct, the velocity could be expressed in terms of certain quantities that could be determined by electromagnetic measurements. This velocity (v) is the ratio of the electromagnetic to the electrostatic unit charge of electricity. Maxwell's electromagnetic theory of light consists in the statement that light-waves are merely electromagnetic waves that have a frequency lying within certain limits determined by the structure of the eye. If this be true, the velocity of light (V) in free space should be equal to the quantity that we have denoted by v. V and v can be measured by direct experiment. Here are some of the results expressed in millions of centimeters per second, with the names of the experimenters responsible for them. The variations in the table

V (Optical)		v (Electrical)	
Foucault	29,836	Ayrton and Perry	29,600
Cornu	29,985	Klemencic	30,150
Michelson	29,976	Rosa	29,993
Newcomb	29,962	Thomson and Searle	29,955

show that it is difficult to measure these quantities with very great precision, but there is no evidence that shows

that one is bigger than the other. The presumption is, therefore, that they are equal, and this is the corner-stone on which the electromagnetic theory of light is based.

After Maxwell, the next great step was made by Hertz about twenty years ago. He succeeded in setting up electric waves (some of them about a foot in length, others a yard or more), and investigated their properties. His famous experiments furnish, perhaps, the most striking evidence that can be adduced in support of Maxwell's theory, as he showed that these electric waves obeyed exactly the laws of light, as Maxwell had predicted they should. He found that they were reflected so that the angle of reflection was equal to that of incidence. He passed them through a large prism of pitch about a yard and a half high, and showed that they were refracted according to Snell's law. He found, too, that, just as with light-waves, he could get polarization and also diffraction. The determination of the speed with which the waves were propagated was a matter of some difficulty, and at first it appeared that they did not travel with the same velocity as does light, but later researches have shown conclusively that they do. Much has been done since Hertz's first experiments to clear away doubts and difficulties, and now an almost complete analogy between electrical and optical phenomena has been *proved by experiment.* Perhaps I should say in passing that these electric waves that Maxwell saw with his powerful mind, and whose properties he predicted, and that Hertz made a commonplace in every physical laboratory, are the same waves that we have all heard so much about in more recent times as employed in wireless telegraphy. They are

popularly associated with the name of Marconi, whose important discovery of the influence of a "grounded wire," immensely extended the range of their effectiveness.

Let us turn now to other evidences of a relation between light and electricity. It has been stated more than once that in free ether, where there is no matter, the velocity of all waves must be the same, whatever be their frequency, and we have already seen that there is a good agreement between theory and observation as to the magnitude of this velocity. When, however, matter is present, the speed of the wave varies with the frequency, as was pointed out at some length in the lecture on dispersion. In that lecture a formula was given connecting the refractive index (n), which determines the speed, and the frequency (f), and if we refer to that formula (p. 66), we see that if f is zero, so that there are no vibrations at all, and everything is steady, we then have $n^2=K$. Now the electromagnetic theory indicates that, under these circumstances, K should be what is known as the specific inductive capacity of the substance that is dealt with. This can be determined from purely *electrical* measurements, and it is important to see how this determination agrees with its value obtained, in accordance with our theory, from *optical* observations. The two substances that have been most carefully examined from this point of view are Rock-salt and Fluorite. The values of K obtained by different observers from electrical experiments on Rock-salt were as follows (the name being that of the experimenter quoted): Curie, 5.85; Thwing, 5.81; Starke, 6.29; the mean being 5.98. The corresponding numbers for Fluorite are: Curie, 6.8; Romich, 6.7; Starke, 6.9; of which the mean is 6.8. The values of

K, calculated from optical experiments in the two cases, are 5.9 and 6.8, so that we have the following comparison: —

Substance	K (Optical)	K (Electrical)
Rock-salt	5.9	5.98
Fluorite	6.8	6.8

Theory also indicates that there is a relation between the reflecting power of a metal and its electrical conductivity, and shows that the reflecting power must depend on the frequency. By observing the electrical conductivities of different metals, we are able to predict what their reflecting powers should be for a given frequency, and to test the theory by actual measurements of these reflecting powers. The following table sets forth some of the results, the numbers expressing the percentage of the incident light that is reflected. The word "light" is used in rather a wide sense, for the frequencies f_1 and f_2 that are dealt with are so low that the waves are far outside the range of the *visible* portion of the spectrum. The frequencies are expressed in million millions per second. It

Metal	$f_1 = 25$		$f_2 = 12$	
	Optical	Electrical	Optical	Electrical
Silver	98.85	98.7	98.87	98.85
Copper	98.4	98.6	98.83	98.73
Zinc	—	—	97.73	97.73
Cadmium	—	—	97.45	97.47
Platinum	96.5	96.5	97.18	97.04
Nickel	95.9	96.4	96.80	96.84

will be observed that the agreement between the optical and electrical estimates of the reflecting power is better for f_2 than for f_1. The explanation of this is that the theoretical formula employed in the computation is only approximately true, the approximation being closer for small frequencies than for large ones.

The various types of evidence for an intimate relation between light and electricity that have so far been referred to are all of a somewhat indirect character, and it would seem reasonable to suppose that there should be some phenomena that would prove more directly that light and electricity have something in common. I have now to direct your attention to evidence of this class. The most elementary knowledge of the science of electricity will make it clear that there is a very close relation between electricity and magnetism. It shows, for example, that an electric current gives rise to a magnetic field, and that a piece of iron can be magnetized by passing an electric current round it. If, then, light and electricity are in any sense one, we should expect a magnetic field to have some influence on light, and one of Faraday's epoch-making discoveries proved that this is the case. Faraday found that when such a uniform transparent substance as glass or carbon bisulphide is placed in a powerful magnetic field, and a beam of plane polarized light is made to traverse the field in the direction of the lines of magnetic force, the *plane of polarization is rotated.* When we dealt in an earlier lecture with a kindred phenomenon exhibited by quartz, solutions of sugar, and other optically active media, we saw that the rotation could be explained once we understood why a wave circularly polarized in the clockwise sense should move through the medium with a different

speed than one polarized counter-clockwise. The same problem presents itself in the explanation of the Faraday effect; but the solution must be quite different, for here we have no peculiarities of structure to deal with that can distinguish the right hand from the left when rotations are concerned. In this case the explanation is afforded by the application of certain well-known laws of electromagnetism which deal with the mutual influence of a current and a magnetic field, and show that different effects are produced by currents flowing in opposite senses, clockwise and counter-clockwise. A precise form is given to the investigation by the adoption of the electron theory, which has already been referred to. According to this the atoms of a substance are made up of groups of electrons, which constitute small charges of electricity, and, when moving round an orbit, have some of the characteristics of an electric current. A careful analysis shows that a right-handed circularly polarized beam should cross the magnetic field at a different rate than a left-handed one, so that a rotation of the plane of polarization is to be expected. It also appears that the amount of the rotation is directly proportional to the length of the field traversed, a law that is similar to that which governs the behavior of optically active media, and one that, like it, has been amply verified by experiment. The theory also indicates that the amount of the rotation depends upon the frequency, so that we have rotatory dispersion, as in the case of active media. The following table records the rotations produced by creosote and carbon bisulphide for different lines in the spectrum, and compares the observed values with the predictions of theory:—

Line in Spectrum	Creosote		Carbon Bisulphide	
	Rotation (theory)	Rotation (observation)	Rotation (theory)	Rotation (observation)
C	0.573	0.573	0.592	0.592
D	0.744	0.758	0.760	0.760
E	0.987	1.000	0.996	1.000
F	1.222	1.241	1.225	1.234
G	1.723	1.723	1.704	1.704

Wood gives the following results for the rotations produced by sodium vapor for different frequencies in the neighborhood of the natural frequencies of sodium. The frequencies (f) are given in million millions per second, and the rotations (R) are those observed, or calculated, to the nearest degree: —

f	R (theory)	R (observation)	f	R (theory)	R (observation)
501	5	5	510	93	90
504	10	10	511	43	43
505	23	20	512	41	40
506	38	40	513	20	20
507	59	66	514	9	10
508	89	90	516	5	5

Theory also indicates, and experiment verifies, that the rotation is in the same absolute direction when the light is travelling from A to B as from B to A. Thus if, to a person at A looking towards B, the rotation appears to be clockwise when the light goes from A to B, then if the light be reflected from B so as to return to A, the rotation

will still appear to A to be clockwise. This leads to a somewhat curious result. The path of a ray of light, no matter how crooked it may be, is usually reversible. If A can see B, then B can see A, and this is true whether they look at one another directly, or whether the light be reflected and refracted at various points in the passage from one to another. You may not be able to see a person directly, and yet you may have a clear view of him by reflection in a mirror; but if this be so, you know that he also can see you in the mirror. Thus, by no ordinary optical device can A see B without B being able also to see A. However, by utilizing this power of rotating

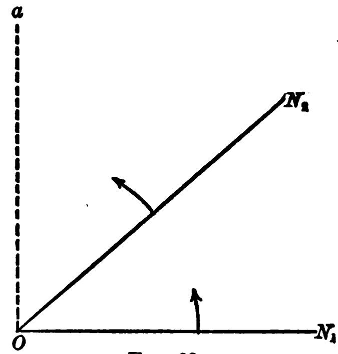


FIG. 69

the plane of polarization possessed by a magnetic field, it is possible to think of an arrangement by means of which B could see A, while A could not see B. Take two Nicol prisms and set them with their principal planes ON_1 and ON_2 (Fig. 69) inclined at an angle of 45°. Place them in a medium in a magnetic field that has just the necessary strength to turn the plane of polarization counter-clockwise, say, through an angle of 45°. The light that goes from A passes through the first Nicol and then is plane polarized, the plane of its polarization being parallel to ON_1. After passing across the magnetic field, this plane is rotated through 45°, and so is parallel to ON_2. The light is thus polarized just in the right plane to pass freely through the second Nicol, so that it reaches B, who will therefore

have no difficulty in seeing A. Now think of the light that sets out from B towards A. On passing through the first Nicol that it reaches, it will be plane polarized, with the plane of its polarization parallel to ON_2. It then enters the magnetic field and, in crossing it, has the plane of its polarization rotated 45° in the direction indicated in the figure. Thus the light is polarized in the direction Oa, which is at right angles to ON_1, so that the light cannot get through the Nicol to reach A. Hence B sees A without A seeing B.

The Faraday effect with which we have been dealing was the first thing of the kind discovered that exhibited a direct action of magnetism on light, but there have been several similar discoveries since. Thus, about thirty years ago, Kerr found that plane polarized light is converted into elliptically polarized light when it is reflected from the polished pole of an electromagnet, under circumstances in which this change could not occur if the field were not magnetic. A few years earlier the same experimenter had discovered another interesting relation between optical and electrical phenomena. He found that a dielectric, like glass, or even a liquid, such as carbon bisulphide, behaves quite differently when in a powerful electric field than when it is not so placed. It acquires the doubly refracting properties of a crystal. This seems to indicate that the electric field has the effect of arranging the electrons in *order*, and so of producing something like the definite structure that gives a crystal different optical qualities in different directions, and accounts for its doubly refracting power.

Even more interesting than the Kerr effect is that of Zeeman, discovered in 1896. He found that a magnetic

field could alter the positions and the character of certain lines in the spectrum. This is a very significant fact, if you bear in mind what has been said as to the position of a line in the spectrum and its relation to the frequency of the vibrations going on within the atom. To alter the frequency, you must interfere with the mechanism of an atom, and Zeeman's discovery proves that you can do this merely by placing the atom in a strong magnetic field. In view of the well-known influence of magnetic forces on electric currents, we may find in the Zeeman effect a powerful support for the electric theory of matter that is a leading feature of recent speculation, and it is mainly because of this that the phenomenon has received so much attention from the world of physical science. Let us see, somewhat more clearly, what the Zeeman effect is (at least in its simplest aspect), and then consider the general outlines of the explanation that has been suggested. We have been reminded that when light from a luminous body in the form of vapor is viewed through a spectroscope, the spectrum is crossed by certain bright lines which have definite and fixed positions for any given substance in a given condition. So well fixed and well known are these lines that, as has been seen, we may readily determine the nature of a substance by noting carefully the positions of these lines. Zeeman's striking discovery was that, when the luminous body was placed in a strong magnetic field, a single line was replaced in some cases by two lines, one on each side of the position of the original line; in other cases by three lines, one in the position of the original, and one on each side thereof. Later researches have revealed more complicated cases, but we shall confine our attention to those that are simplest.

Without entering too much into technicalities, let me indicate the explanation afforded by Lorenz of the simplest case of the Zeeman effect. The fundamental idea is that which lies at the root of the electric theory of matter. It supposes that, in its last analysis, an atom of matter would be found to consist of a number of moving charges of electricity, which now usually go by the name of *electrons*. Theory indicates and experience proves that a

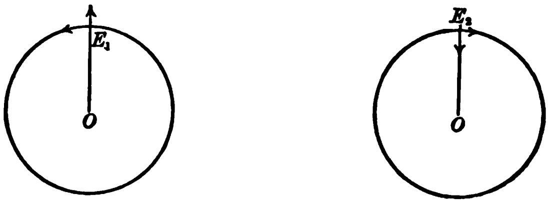


FIG. 70

charge of electricity moving rapidly round a closed orbit has an effect similar to that of an electric current flowing in the same circuit. Now it is one of the most widely known and most firmly established laws of electromagnetism that a current is affected by the presence of a magnetic field, so that we have good reason to suppose that an electron moving in an orbit would be affected by such a field. Moreover, certain laws of electromagnetism that are well grounded in experience enable us to predict *how* the electron would be affected in any given circumstances. Consider the simple case of an electron moving steadily in a circle, say in the plane of this paper round O as a center. (Fig. 70.) As the electron might move round in two senses, clockwise or counter-clockwise, there will be two cases to deal with, and we may distinguish these electrons by the letters E_1 and E_2. If the magnetic force is at right

angles to the plane of the paper, it follows from the laws of electromagnetism that E_1 will be driven along OE_1, *away from the center*, while E_2 will be pulled along E_2O *towards the center*. It is a simple deduction from this that the frequency of the vibrations of E_2 will be increased, while that of E_1 will be diminished. You know, doubtless, that if you make a stone describe a circle by whirling it round at the end of a string, the force with which you have to pull the string is greater, the greater the number of revolutions per minute, *i.e.* the greater the frequency. Thus an increased force towards the center means a greater frequency and a diminished force towards the center means a smaller frequency. Now when there are no external magnetic forces present the electrons E_1 and E_2 are drawn towards O with a certain force that depends on the distribution of the electrons in that neighborhood. The presence of a magnetic field adds a new force away from O in the case of E_1, and towards O in the case of E_2, so that the total force towards O is diminished for E_1 and increased for E_2, and thus the frequency is diminished for E_1 and increased for E_2. It thus appears that the effect of placing a number of rotating electrons in a magnetic field would be that those electrons whose planes of motion were at right angles to the lines of magnetic force would have their frequencies increased or diminished according to the sense (clockwise or counter-clockwise) in which their orbits were described. Thus the original single line in the spectrum would be replaced by a doublet, the members of which would be on opposite sides of the original line. At the same time those electrons that were moving in the same plane as the lines of magnetic force would not be affected, so that their frequency would be un-

changed. Not only does Lorenz's explanation account for the main feature of the phenomenon, that is, for the production of two or of three lines from a single line, according to the direction of the lines of magnetic force, but it also indicates the state of polarization of the different lines. It shows that the two lines of a doublet should be circularly polarized, one being right-handed and the other left-handed. It shows also that with a triplet the middle line should be polarized in a plane perpendicular to the direction of the magnetic force, and the two outer lines polarized in a plane parallel to that direction. All these details with reference to the nature of the polarization of the different lines were first predicted by Lorenz's theory, and later observation proved them to be correct.

It should perhaps be stated that later researches have proved that in many instances the influence of a magnetic field on the character of the spectral lines is much more complex than what was first observed by Zeeman. There are many indications that if an atom be rightly regarded as a group of electrons, the distribution and motion of these must constitute a mechanism that is far from simple, and the complexity of certain aspects of the Zeeman effect is what might well be expected. It would be out of place to enter into such questions here, but before taking leave of the Zeeman effect I should like to call your attention to a very interesting application of the theory that has been made quite recently by Hale. It has long been known that there is an intimate relation between electricity and magnetism. You have been reminded within the last few minutes of the influence on a current of a magnetic field, and you know probably that a current by itself sets up a magnetic field, that is, that there are certain mag-

netic effects due merely to the presence of an electric current. If, then, a moving charge of electricity is, under any circumstances, equivalent to a current, it should also give rise to a magnetic field, as Maxwell anticipated and as, in fact, Rowland proved by experiment as long ago as 1876. Now the ingenious device of Hale referred to on p. 88 of the lecture on Spectroscopy, by means of which he takes photographs of the Sun with light from a single line in the spectrum, *e.g.* one of the lines of hydrogen, quickly led in his hands to many interesting discoveries. It made it clear, amongst other things, that there are numerous vortices or whirlwinds in the solar atmosphere, and such is the detail in some of the photographs that it seems possible to determine, from the form of the streamers round the whirlwind, in what sense (clockwise or counter-clockwise) the vortex is rotating. These whirlwinds are characteristic of Sun-spots, and it seems probable that all such spots are vortices spinning in the solar atmosphere.

We know from numerous terrestrial experiments that at high temperatures carbon and many other elements that occur in the Sun send out large numbers of corpuscles charged with electricity. It is natural to suppose that the same thing will happen under similar circumstances in the Sun. Let us suppose, further, that in any region near a Sun-spot a preponderance, say, of negative charges exists. These will be whirled round in the vortex, and as they move round will constitute effectively an electric current, and so give rise to a magnetic field. We should expect, then, that if our hypotheses be justifiable, a Sun-spot should be characterized by the presence of a magnetic field. One way of detecting this presence is to make careful observations of the features of the lines of the spectrum

in this region, and see if we can find evidence of the Zeeman effect. It had been known for some time that the spectrum of a Sun-spot differs in several respects from the ordinary solar spectrum. Amongst the peculiarities of a Sun-spot spectrum are two that are specially significant in view of the Zeeman effect: in the first place, a large number of doublets, or double lines, exist; and secondly, many of the lines are unusually broad. These are just the features that we should expect, from our knowledge of the Zeeman effect, provided we see the force of the reasons that have been adduced, or of any other reasons, for expecting a strong magnetic field near a Sun-spot rather than in other regions of the Solar atmosphere.

Prompted by some such reasons as these, Hale recently devoted the resources of the Mt. Wilson Observatory to the problem of examining the spectral lines in Sun-spots, keeping an especially sharp lookout for evidences of the Zeeman effect. He found that the light from the two edges of certain lines was circularly polarized in opposite directions. He found that right- and left-handed polarizations were interchanged in passing from a vortex spinning clockwise to one spinning in the opposite sense. He found also that the displacements of the widened lines had just the same features as those detected by Zeeman. With the caution of a man of science he concluded that the existence of a magnetic field in Sun-spots was "probable." By experimenting in his laboratory on the strength of field necessary to produce a shift of the spectral lines of the same amount as those observed in the Sun-spots, he was enabled to form some estimate of the strength of the magnetic field in these spots.

Here, then, we have a striking example of the breaking

down of barriers that earlier thinkers have set up between different fields of knowledge. Astronomy, chemistry, electricity, magnetism, and light have each had fences raised around them. In these researches of Hale's you have observations that seem to deal only with *light*, observations, namely, of the varying intensity of the light in different places. Some portions of the field of view are very bright, others seem relatively dark, and present the appearance of dark lines of different widths in different positions. From these you are enabled to determine certain facts of *astronomy*, to learn something definite as to the physical condition of the Sun. You also learn something of *chemistry*, for you can tell, with practical certainty, that you are looking at iron, or chromium, or manganese, or vanadium. *Electricity*, too, is brought before your view, for you are forced to consider the effect of electric charges caught up in the whirl of the great solar vortices. Finally, these observations on light lead you inevitably into the field of *magnetism*, and even enable you to estimate the strength of the magnetic forces that play about the surface of the Sun, although they are nearly a hundred million miles away.

Thus science is, after all, a unity, and in this key I may appropriately bring this course of lectures to a close. Science strives to bring all things, with whatever names they may have been labelled in the past, into harmony with some all-pervading principle or law. "Give me extension and motion," exclaimed Descartes, "and I will construct the world!" "Give me ether and electrons and the fundamental laws of mechanics," says the modern physicist, "and I will give you a picture of the world that is beautiful in its simplicity and in its faithfulness. I will

not, however, pretend to *explain* the world, and I will leave questions of reality and of purpose for others to dispute over." Perhaps it should be remarked that this method of the modern man of science differs essentially from what is sometimes called the metaphysical method. I have no intention of saying anything against metaphysics. It would be an impertinence to do so, and I am ready to admit that the remarks of scientists about metaphysicians are often quite as valueless as those of metaphysicians about science. All that need be said is that physicists do not even attempt to evolve the laws that govern the world from their own consciousness. Their knowledge is strictly empirical, their hypotheses and "laws" are valued only so far as they harmonize experiences and fit the facts together. Everywhere these laws must be put to this test, and if they fail to satisfy it, they must be ruthlessly abandoned. My aim throughout has been to show you how well the modern theory of light serves its purpose and actually fits the facts, and I hope that I have succeeded in giving you some conception of its comprehensiveness and power, even if I have not revealed its true nature as a noble work of art.

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